Preprint

THE TEMPERATURE STRESS DAY INDEX--
A PLANT WATER STATUS INDICATOR

by K. L. Clawson and R. D. Jackson

U.S. Department of Agriculture, Agricultural Research Service, U.S. Water Conservation Laboratory, 4331 East Broadway Road, Phoenix, AZ 85040

ABSTRACT

The temperature stress day (TSD), defined as the difference in temperature of a well-watered and a water-stressed canopy, has been widely accepted. However, its dependence on vapor pressure (VPD) has never before been reported. The VPD dependence was proven both theoretically and empirically using the Penman-Monteith resistance equation and the non-water-stressed baseline equation relating canopy and air temperatures to VPD. The VPD effect on the canopy temperature difference was accounted for in a new plant water status indicator based on the TSD called the temperature stress day index (TSDI). The TSDI was defined as:

$$TSDI = \frac{T_c - T_{cL}}{T_{cu} - T_{cL}}$$

where T_c is the measured canopy temperature, T_{cL} is the canopy temperature expected of a fully well-watered crop, and T_{cu} is the canopy temperature expected of a fully water-stressed crop. T_{cL} and T_{cu} were also defined theoretically and empirically and compared to measured T_{cL} and T_{cu} values for alfalfa grown under both well-watered and water-stressed conditions. Calculated values closely approximated measured values indicating that the linear ratio of canopy temperatures used in the TSDI provides a good method for quantification of plant water stress.

INTRODUCTION

Detection of water stress by remote sensing techniques has been the subject of many studies beginning with Monteith and Szeicz (1962) and Tanner (1963). These scientists applied the then new science of infrared thermometry to the measurement of plant temperature which was reported to be an indicator of plant water status in the early 20th century (Miller and Saunders, 1923). Development of portable infrared thermometers since that time has led to the proliferation of their use. Subsequently, crop water stress indicies which utilize canopy temperature have been developed. Some of the indicies now in use include: the crop water stress index or CWSI developed empirically by Idso et al. (1981) and substantiated theoretically by Jackson et al. (1981), and the temperature difference between a well-watered canopy and a water stressed canopy called the temperature stress day (TSD; Gardner et al, 1981). Operational use of the empirical CWSI requires concurrent measurements of canopy and air temperature and of the water vapor pressure deficit of the air. Use of the TSD requires concurrent measurements of the canopy temperature of a well-watered field and of the field of interest. The TSD was said to be advantageous over CWSI in stress detection since TSD was thought to be independent of the environmental factors upon which CWSI is based (Jackson, 1982). Still, the CWSI has become more widely accepted since well-watered fields are not always available as required by the TSD. Furthermore, there was no specified upper limit to which a TSD value might rise. Hence, no absolute level of stress could be calculated through the TSD.

This treatise will discuss the development of an upper limit for the TSD, and a crop water status index will be developed from those ideas. We will also show that the TSD method is, contrary to current opinion, dependent on the same environmental variables as the CWSI. The approach will be both empirical and theoretical.

Theoretical Considerations

The energy balance of a crop can be written

$$R_n = LE + H + G \qquad 1$$

where R_n is net radiation, LE and H are the latent and sensible heat fluxes, respectively, and G is the soil heat flux (all terms expressed as W m^{-2}). Following the electrical resistance analog of Monteith (1973) and modified by Verma and Barfield (1979), LE and H can be expressed as

$$LE = \frac{\rho C_p}{\gamma} \frac{(e_c^* - e_a)}{(r_c + r_{av})} \qquad 2$$

$$H = \rho C_p \frac{(T_c - T_a)}{r_{as}} \qquad 3$$

where ρ is the density of air (kg m^{-3}), C_p is the specific heat of air at constant pressure (J kg^{-1} C), γ is the psychrometric constant (kPa C^{-1}), e_c is the saturated vapor pressure (kPa) evaluated at canopy temperature (T_c, units of C), e_a is the actual vapor pressure of the air (kPa) evaluated at the air temperature (T_a, units of C), r_c is the canopy resistance (s m^{-1}) and r_{av} and r_{as} are the aerodynamic resistances to the fluxes of water vapor and heat (s m^{-1}), respectively.

By substituting the identities of H and LE into Eqn. 1, setting G=0, and assuming equality of r_{av} and r_{as}, Tc can be determined by

$$T_c = T_a + \frac{R_n\ r_a}{\rho C_p} \cdot \frac{\gamma(1+r_c/r_a)}{\Delta+\gamma(1+r_c/r_a)} - \frac{(\overset{*}{e}_a-e_a)}{\Delta+\gamma(1+r_c/r_a)} \qquad 4$$

It is obvious from Eqn. 4 that T_c depends on air temperature, net radiation, water vapor pressure deficit (VPD) of the air, and the aerodynamic and canopy resistances.

From Eqn. 4, we can define an upper and a lower limit of T_c for a given T_a, R_n, e_a, r_a and r_c. For the maximum upper limit of T_c (T_{cu}) at which no transpiration occurs, r_c approaches infinity. Eqn. 4 then simplifies to

$$T_{cu} = T_a + \frac{R_n\ r_a}{\rho C_p} \qquad 5$$

indicating energy exchanges of only radiation and sensible heat. The result (Fig. 1) is a straight line relationship between T_{cu} and T_a at a given R_n and r_a. For a crop well supplied with water, the potential lower limit of T_c (T_{cL}) can be determined in a similar manner. This is done by setting r_c to zero; the case of the plant acting as a free water surface. Eqn. 4 can then be expressed as

$$T_{cL} = T_a + \frac{R_n\ r_a}{\rho Cp} \cdot \frac{\gamma}{\Delta+\gamma} - \frac{(\overset{*}{e}_a-e_a)}{\Delta+\gamma} \qquad 6$$

A family of curves can be generated from Eqn. 6 as a function of T_a and relative humidity (e_a/e_a^*). These curvilinear relationships are shown in Fig. 1 with relative humidity ranging from 0 to 100%. The most accurate solution to Eqn. 6 requires iteration by evaluating Δ at $(T_{cL} + T_a)/2$. At 100% relative humidity, T_{cL} approaches T_{cu} but remains 2 to 4 C lower than T_{cu}. This occurs because canopy temperature becomes warmer than air temperature. Since the canopy is warmer than air temperature, the saturated vapor pressure at the crop surface is larger than the saturated vapor pressure evaluated at T_c. A vapor pressure gradient still remains between the crop and the air. As a result, transpiration still continues in saturated air to cool the crop below T_{cu} but not below T_a.

The TSD can now be defined in terms of the controlling parameters which specify T_c and T_{cL}, namely by combining Eqns. 4 and 6 such that

$$TSD = T_c - T_{cL} = \frac{R_n\ r_a}{\rho C_p} \left[\frac{\gamma(1+r_c/r_a)}{\Delta+\gamma(1+r_c/r_a)} - \frac{\gamma}{\Delta+\gamma}\right]$$

$$+ (e_a^*-e_a) \left[\frac{1}{\Delta+\gamma} - \frac{1}{\Delta+\gamma(1+r_c/r_a)}\right] \qquad 7$$

When T_c is measured, Eqn. 7 can be simplified to

$$TSD = T_c - T_{cL} = T_c - \frac{R_n\ r_a}{\rho Cp} \cdot \frac{\gamma}{\Delta+\gamma} - \frac{(e_a^* - e_a)}{\Delta+\gamma} \qquad 8$$

Since both R_n and VPD vary diurnally and day-to-day, an identical value of TSD obtained from different days or even different hours may not necessarily indicate the same level of stress. For example, by altering

relative humidity by only 25% (from 25 to 50%) at T_a=30 C, the lower canopy temperature limit rises from 18.5 C to 23.4 C--a difference of 4.9 C. As a result, TSD changes by 4.9 C. This illustrates that TSD cannot be considered to be independent of environmental conditions. In order to be useful, TSD must be normalized in such a manner that these conditions can be accounted for. This process is described in the succeeding paragraphs.

A maximum canopy temperature difference expected of a water stressed crop above that of a well-watered crop is determined from the appropriate combination of Eqns. 5 and 6 such that

$$T_{cu} - T_{cL} = \frac{R_n\, r_a}{\rho C_p} \left[1 - \frac{\gamma}{\Delta+\gamma}\right] + \frac{(e_a^* - e_a)}{\Delta+\gamma} \qquad 9$$

Air temperature no longer appears explicitly in the formula, but appears implicitly in Δ e_a^*, and e_a. The resulting solution, plotted now as a function of relative humidity, is shown in Fig. 2. The area under each curve is the range where measured canopy temperature differences are expected to occur at a specific relative humidity or VPD.

The values obtained from Eqn. 9 represent the maximum theoretical canopy temperature difference which would be expected when a fully well-watered canopy is compared to a fully water-stressed canopy. However, the assumption that canopy resistance is negligible under well-watered conditions is rarely accurate (van Bavel and Ehrler, 1968). A more realistic representation is found by

Several variables are required as inputs to Eqn. 11, some of which are difficult to obtain. However TcL is, in practice, concurrently measured with T_c. When this is done, Eqn. 9 simplifies to

$$TSDI = \frac{T_c - T_{cL}}{T_a + \frac{R_n\ r_a}{\rho C_p} - T_{cL}} \qquad 12$$

In this simplified form, the TSDI requires only net radiation, air temperature and aerodynamic resistance values as well as the two canopy temperatures T_c and T_{cL}. The need for measurements of relative humidity or VPD and r_{cL} are obviated. Measurement of R_n, T_a, T_c and T_{cL} are straightforward while r_a can be estimated by several methods such as those described in Jackson et al (1981) and Heilman and Kanemasu (1976) among others.

The operational use of the theoretically derived TSDI can be illustrated using both the theoretical upper and lower canopy temperature limits. By specifying T_a, R_n, r_a, and r_c, a family of TSDI curves can be generated as shown in Fig. 3. For example, if T_c=27.0 C and VPD=3 kPa, then the TSDI would be 0.48.

Empirical Approach

The empirical development of the TSDI follows closely the empirical development of the CWSI. The basis of the CWSI lies in the concept of a linear relationship of the canopy-air temperature difference (T_c-T_a) as a function of vapor pressure deficit when the crop has ample water (Ehrler, 1973). The basic form of the relationship is

$$T_{cL} - T_a = b + m(e_a^* - e_a) \qquad 13$$

where b and m are coefficients for the intercept and slope, respectively. All well-watered plant species studied to date have been reported to exhibit a unique T_{cL}-T_a vs. VPD relationship (Idso, 1982). The empirical CWSI was born from a knowledge of these so-called "non-water-stressed baseline" relationships and the limit which T_c-T_a approaches in the complete absence of transpirational cooling (Idso et al, 1981). The upper limit, according to Pinter (1983) is a function of the well-watered baseline and can be expressed by

$$T_{cu} - T_a = b + m(e_a^* - e_{a+b}^*) \qquad 14$$

where e_{a+b}^* is the value of the saturation vapor pressure at $T_a + b$. The lower and upper limit equations can be easily rearranged making direct calculation of T_{cu} and T_{cL} possible. When Eqns. 13 and 14 are combined, the maximum temperature difference between a fully water stressed canopy and a fully well-watered canopy can be determined such that

$$T_{cu} - T_{cL} = m\,[(e_a^* - e_{a+b}^*) - (e_a^* - e_a)] \qquad 15$$

This TSD, calculated empirically, also emphasizes the dependence of the canopy temperature difference on VPD.

From these empirical relationships, the TSDI can be readily constructed in the following manner:

$$TSDI = \frac{T_c - T_{cL}}{T_{cu} - T_{cL}} = \frac{T_c - T_a - b - m(e_a^* - e_a)}{m\,[(e_a^* - e_{a+b}^*) - (e_a^* - e_a)]} \qquad 16$$

An a priori knowledge of the non-water-stressed baseline is required before the TSDI can be empirically determined. In this form, the empirically derived TSDI and the empirically derived CWSI are identical. When T_c and T_{cL} are both measured, only knowledge of the upper limit is required. Eqn. 16 then simplifies to

$$TSDI = \frac{T_c - T_{cL}}{T_a - T_{cL} + b + m(e_a^* - e_{a+b}^*)} \qquad 17$$

An example of the operational use of the empirical TSDI is illustrated in Fig. 4 for alfalfa (Meticago sativa L.) at T_a=30 C. At a VPD of 3 kPA, a measured canopy temperature of 27 C would equate to a TSDI value of 0.37.

MATERIALS AND METHODS

Experimental verification of the TSDI was conducted from 15 Nov 1984 through 09 Jul 1985 on a one-year-old stand of alfalfa (Meticago sativa L., cv. Lew) grown in Phoenix, Arizona. The soil is a fine, loamy, mixed, calcareous, hyperthermic Anthropic Torrifluvent. The 0.5 ha field was divided into 18 plots ranging in size from 160 to 325 m^2. The plots were arranged in 6 blocks of 3 plots each and 3 irrigation treatments were randomly imposed on two of the blocks during each growth cycle. The 5 growth cycles were determined by the cutting dates, which were 15 Nov 1984 and 12 Feb, 28 Mar, 07 May, 06 Jun, and 09 Jul 1985. The irrigation treatments were designated Early, Late and Dry and were designed to distribute the imposed water stress through different periods of a growth cycle. The Early irrigation treatment was irrigated within 3 days after harvest to field capacity at a depth of 0.9 m, but received no further supplemental

irrigations. A shallow irrigation was an assurance of stress development later in the growing cycle. The Late treatment was irrigated to field capacity at a depth of 3 m halfway through the growth cycle but received no initial irrigation following harvest. The Dry treatment received no irrigation water from harvest to harvest. Following harvest, the irrigation treatments were rotated to two new blocks to avoid any cumulative stress affects on stand density. In addition to the three deficit irrigation treatments, two Wet or fully irigated treatments were maintained in two of the remaining non-treatment blocks. These plots were irrigated immediately after harvest and whenever the soil water content, as determined by thrice-weekly neutron probe measurements, declined to 50% of field capacity in the top 3 m of soil.

Canopy temperature (Everest Interscience,[1/] model 110, 4° FOV) and concurrent air temperature, vapor pressure deficit (Bendix psychrometer,[1/] model 566) and net radiation (Fritschen; 1963, 1965) measurements were made daily at 1330 hrs MST under full sun and ground cover conditions. Canopy temperature of each plot was measured from the four cardinal directions was determined at six different sites per view direction. The infrared thermometer was held at a declination angle of 30° from the horizontal resulting in a spot size of about 0.25 m^2. Psychrometric observations collected both immediately preceding and following the canopy temperature measurements were averaged to give mean air temperature and vapor pressure deficit. Net radiometers placed in 6 plots (both treatment

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[1/] Trade names and company names are included for the benefit of the reader and do not imply any endorsement or preferential treatment of the product listed by the U.S. Department of Agriculture.

and nontreatment plots) at a height of 1.5 m were scanned automatically every 1.5 min during canopy temperature measurements. These data were time averaged over a 30 minute period to give a mean net radiation value.

Study-long empirical and theoretical values of T_{cL} and T_{cu} were calculated and compared to measured values. Non-water-stressed baselines for each growing cycle and for the entire study were computed according to Eqn. 13 from the daily midday observations of canopy and air temperature and vapor pressure in the Wet plots. In addition, a single diurnal observation of these variables, recorded every 30 min from 1000 through 1600 hours MST, was also included in the computation of the non-water-stressed baseline for each growth cycle. These baselines were compared to those reported by Idso et al (1981) for alfalfa.

RESULTS AND DISCUSSION

The six month period of measurement provided an opportunity for large ranges of air and canopy temperature, net radiation and vapor pressure deficit to be observed through five growth cycles. Air temperature at the time of canopy temperature measurements ranged from a minimum of 14.7 to a maximum of 40.3 C during the course of the study. Concurrent values of net radiation ranged from 310 to 720 W m^{-2} and VPD ranged from 0.89 to 6.59 kPa. The response of measured canopy temperature to these three environmental parameters and to the imposed water stress is evident in Fig. 5. These data are plotted for only clear sky conditions and when canopy cover was 100% developed. Maximum values of T_c at a given T_a represent T_{cu} while minimum values of T_c represent T_{cL}. Little spread was observed in canopy temperature at air temperatures less than 25 C. These air temperatures

represent the winter months when precipitation events occurred frequently and no water stress developed. Hence, no T_{cu} values were recorded during this time period. The wet climate and cool air temperatures were also conducive to the growth of downy mildew (Peronospora trifoliorum d By.) and blue alfalfa aphids (Acyrthosiphon kondoi Shinji) and these two pests were prevalent during the Jan-Feb growing period. The probable result was a warmer Wet canopy temperature than would otherwise have been expected. Therefore, no values of T_{cL} or T_{cu} were recorded during the winter months. No infestation of either mildew or aphids was observed during the warmer and drier period of Mar-July. Rainfall during the latter period (T_a > 25 C) was also insufficient for optimum growth and severe water stress was visually inferred from plant wilting and leaf abscission. The large spread in canopy temperature was recorded at air temperatures >25 C and differences (Dry-Wet) as large as 10 C were measured. Maximum and minimum T_c during this time period were considered to be representative of T_{cu} and T_{cL}, respectively.

Empirically derived TcL and Tcu are shown for the entire study in Fig. 5. In order to plot T_{cL} and T_{cu} as a function of T_a, VPD was first calculated as a function of T_a as shown in Fig 6. A simple second order polynomial equation with an R^2 of 0.980 adequately specified the T_a:VPD relationship. With the T_a:VPD prediction equation, T_{cL} was computed using Eqn. 13 with the slope and intercept values for alfalfa reported by Idso et al (1981). Empirical T_{cu} was obtained in a similar manner using Eqn. 14. The calculated values of T_{cL} and T_{cu} fit closely the measured minimum and maximum canopy temperatures. However, empirical estimates of T_{cL} and T_{cu}

were in closer agreement to measured values when slope and intercept coefficients, calculated from Eqn. 13 with Wet data, were used. These coefficients are summarized in Table 1 for each growth cycle and for the entire study. The study-long coefficients were also used to calculate empirical T_{cL} and T_{cu}, which are plotted in Fig. 5 along with the T_{cL} and T_{cu} derived from Idso et al (1981).

The general seasonal trend observed in the coefficients was for the slope to become decreasingly negative and for the intercept to decline, even becoming negative as the season progressed. This finding is in opposition to Idso (1982) who stated that no negative intercepts had been recorded for 26 different plant species, among them alfalfa. The slopes and intercepts obtained during the two growth cycles between 28 Mar and 06 Jun most closely approximated the Idso et al (1981) baseline. It was during this same time of year that the data for their baseline, grown at the same location, was collected.

The time-of-year dependent baselines shown for this study were well correlated to VPD (see Table 1). The changing slopes and intercepts suggest a curvilinear relationship of T_c-T_a with VPD. This is precisely the finding of Jackson et al (1981) in their theoretical approach to the calculation of T_c-T_a. Kirkham et al (1983) also indicated that the range of VPD greatly affected the slope and intercept of the non-water-stressed baseline. Indeed, regression analysis of a second order polynomial fit to our data showed the higher order equation to be significant ($P \leq 0.05$) with the equation being $T_c-T_a = 4.04 - 3.17(VPD) + 0.142(VPD)^2$. Coefficient of determination for the fit was 0.937.

We conclude, therefore, that different coefficients for the linear relationship of T_c-T_a vs. VPD can be obtained in different seasons or in different climates, depending on the range of VPD over which the relationship is derived. We conclude further, that net radiation plays only a minor role in the T_c-T_a vs. VPD relationship as demonstrated by the goodness of fit of the calculated empirical T_{cL} shown in Fig. 5. And finally, the empirical approach to the calculation of T_{cL} and T_{cu} is sufficiently accurate to justify its use.

Once T_{cL} and T_{cu} are determined empirically, they can be used in the TSDI. Any measured T_c will fall between these two temperature extremes. The TSDI, as defined by Eqn. 16, assigns a relative stress level according to the distance T_c is removed from the T_{cL} baseline.

Theoretical T_{cL} and T_{cu}, plotted together with data from the study, are shown in Fig. 7. T_{cu} was obtained from Eqn. 5 by first setting a nominal value for R_n at 600 W m^{-2} and then iterating to find r_a such that the line closely approximated the maximum observed value of T_c at a specific T_a. A similar approach was described by Jackson et al (1981) who applied the technique to determine r_a in wheat (Triticum durum Desf.). The r_a value obtained for alfalfa using this approach was 6 s m^{-1}. While this value appears to be small, it is not inconsistent with r_a values for other crops which were obtained in a similar manner. Jackson et al (1981) reported a value of 10 s m^{-1} for wheat and Idso et al (1986) reported a value of 24 s m^{-1} for water hyacinth (Eichhornia crassipes (Mart). Solms). Since r_a is largely a function of canopy characteristics, and with leaf size being a primary factor of any canopy characteristic, it follows that

the lowest value of r_a would be reported for alfalfa and that water hyacinth would have the largest r_a. Wheat, with an intermediate leaf size, would fall somewhere between the two extremes.

After computation of r_a, r_c was determined in a similar manner to that described for r_a using Eqn. 4, The T_a:VPD relationship previously described was used to obtain values of VPD at a given T_a and a value of 600 W m^{-2} was used for net radiation. Canopy resistance was determined iteratively by substituting values of r_c into the equation to make the line fall through the minimum T_c values. A value of 15 s m^{-1} for r_c provided the best fit. The iterative calculation of r_a and r_c provided a good fit of T_{cL} to the data for the entire range of T_a. The same was true for T_{cu} during the time period when stress was evident (T_a>25 C).

Net radiation enters into each equation for T_{cL} and T_{cu}. Since R_n was not constant throughout the study, the upper and lower values of R_n (310 and 720 W m^{-2}, respectively) were used to indicate the extremes of T_{cu} and T_{cL}. Changing net radiation by approximately 400 W m^{-2} altered T_{cL} by only 1.0 C and T_{cu} was altered by only 2.0 C at a T_a of 40 C. This indicates that net radiation served only a trivial role in the determination of T_{cL} and T_{cu}.

Once appropriate values of r_a and r_c have been determined, and the theoretical values of T_{cL} and T_{cu} have been calculated from measured values of T_a, VPD, and R_n, a relative stress value can be assigned to any measured T_c via the theoretical TSDI.

CONCLUSIONS

The temperature stress day was proven, both empirically and theoretically, to be dependent on VPD. As such the TSD is unacceptable for use in stress detection when a constant VPD cannot be maintained. Instead, the TSDI was proposed as a means to account for this dependence. In order to calculate a TSDI, some knowledge of the expected minimum and maximum canopy temperature extremes at a given air temperature and vapor pressure deficit is required. Both theoretical and empirical methods for the derivation of these two extremes were presented. The calculated extremes were compared to measured extremes and both the theoretical and empirical values were in good agreement. As such, the TSDI appears to be a viable approach to remote monitoring of water stress.

Some limitations to its use are evident for both the theoretical and empirical approaches. In the case of the theoretical approach, values of r_a and r_c are, in practice, difficult to obtain. Inaccurate estimates of either or both parameters alter the predicted T_{cL} and T_{cu}, thus affecting the TSDI. In the case of the empirical approach, an a priori knowledge of the baseline coefficients is needed before the TSDI can be used. However, many of these limitations can be avoided if the TSDI is applied to thermal data obtained either from either aircraft or satellites. Minimum canopy temperatures for the TSDI would not need to be calculated in this case, but could be determined from measured T_c values. The coolest canopy temperatures measured from an airborne platform could be assumed to represent T_{cL}, particularly in an irrigated area. This assumption would obviate the need for r_c and VPD, the former being particularly troublesome to

determine. Only maximum canopy temperatures would need to be estimated according to Eqn. 5, and R_n can be determined from the same platform (Jackson et al, 1985) as the temperature data. Ground measurements of T_a could be obtained from automated weather data collection networks similar to that in operation in Nebraska (Hubbard et al, 1983) and estimates of r_a could be obtained in a similar manner reported here. T_{cu} could then be rapidly calculated. Only this simplified data set would be needed to calculate TSDI, as specified in Eqn. 12, which could then be used to assess the relative water stress for entire fields or farms. Irrigation scheduling on a grand scale based on canopy temperatures could be adopted.

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Table 1. Results of linear regression analysis for $T_{cL}-T_a$ vs. VPD. Temperature is in units of Celcius and VPD is in units of kPa.

Time period	slope	intercept	R^{2*}	n	$S_{y \cdot x}$	S_s	S_i	VPD range
15 Nov - 12 Feb	----------diseased canopy----------							
12 Feb - 28 Mar	-2.64	4.06	0.763	47	0.557	0.220	0.452	1.26 - 2.47
28 Mar - 07 May	-1.87	1.43	0.888	102	0.606	0.066	0.242	1.66 - 4.84
07 May - 06 Jun	-1.99	1.01	0.883	42	0.436	0.114	0.381	2.27 - 4.65
06 Jun - 09 Jul	-1.60	-0.33	0.730	81	0.805	0.109	0.623	3.69 - 6.59
All data	-2.02	2.04	0.926	272	0.851	0.035	0.144	1.26 - 6.59

* R^2 = coefficient of determination

n = number of observations

$S_{y \cdot x}$ = standard error of the estimate of y on x

S_s = standard error of the slope estimate

S_i = standard error of the intercept estimate.

LIST OF FIGURES

Fig. 1. Theoretically derived upper and lower canopy temperatures specified by Eqns. 5 and 6 where R_n = 600 W m^{-2} and r_a = 10 s m^{-1}.

Fig. 2. Theoretically derived canopy temperature difference (T_{cu}-T_{cL}) specified by Eqn. 9 where R_n = 600 W m^{-2} and r_a = 10 s m^{-1}.

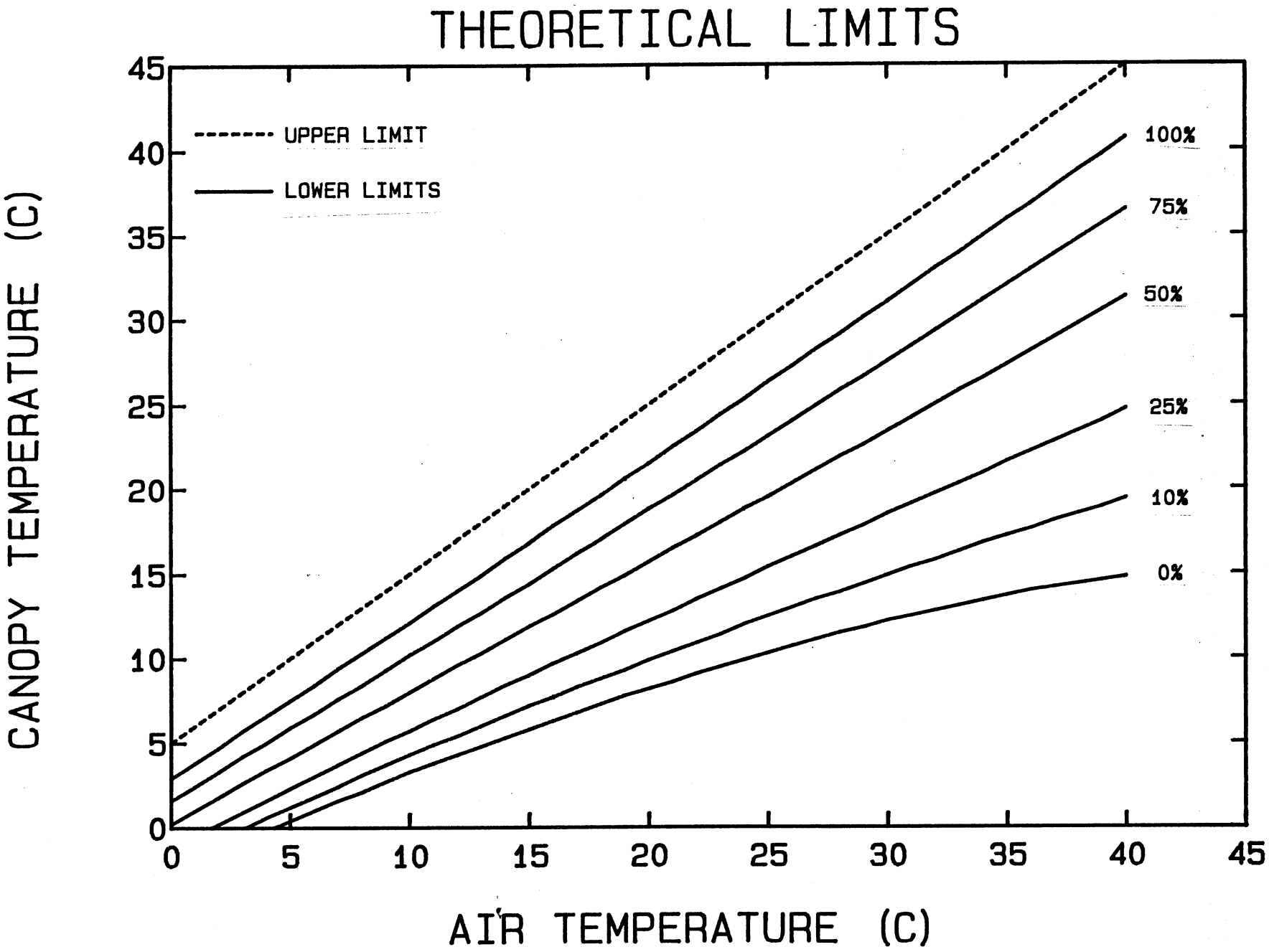
Fig. 3. Theoretically derived TSDI specified by Eqn. 11 where R_n = 600 W m^{-2}, r_a 10 s m^{-1}, r_c = 0 s m^{-1} and T_a = 30 C.

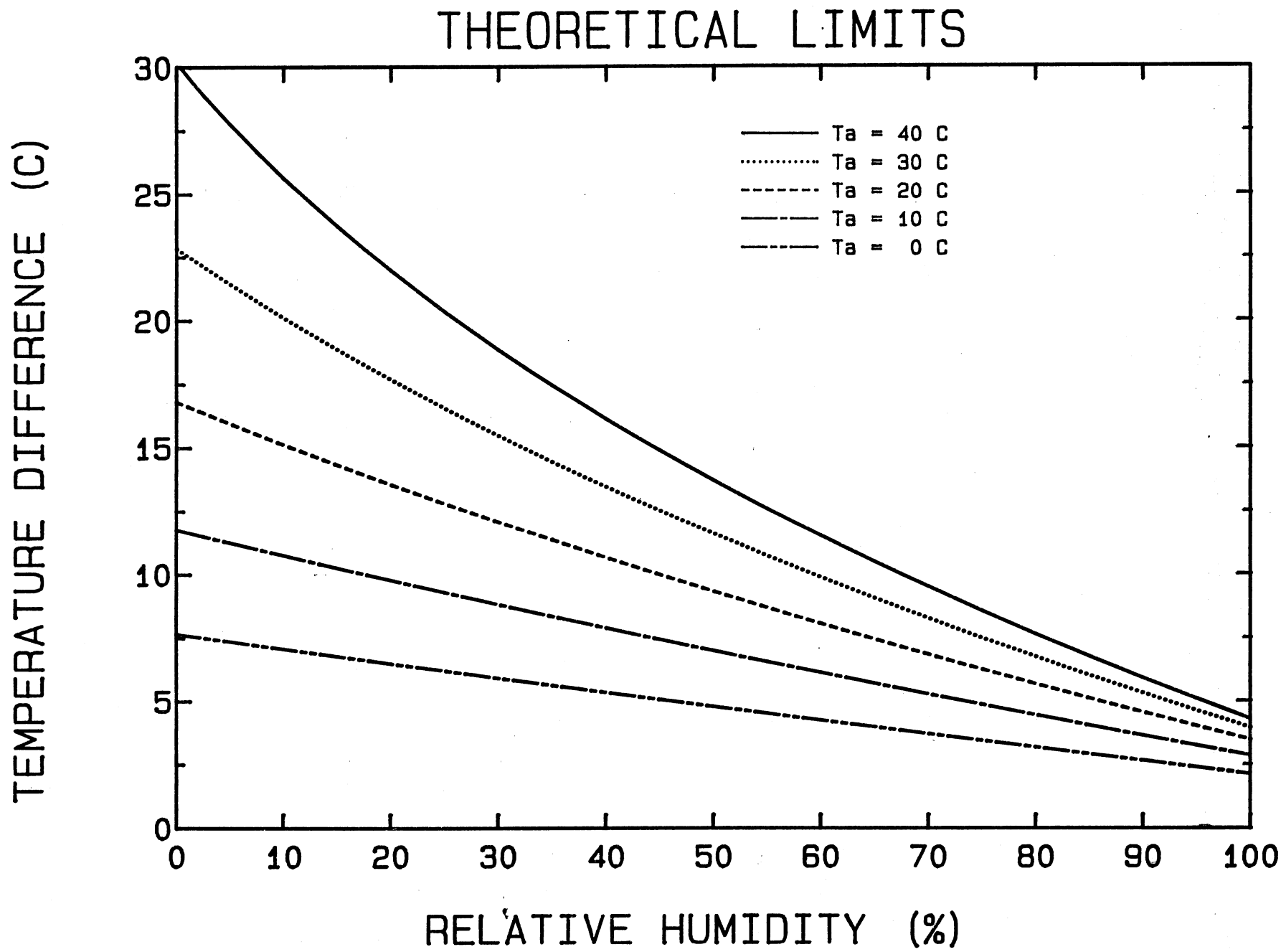
Fig. 4. Empirically derived TSDI specified by Eqn. 16 using coefficients from the non-water-stressed baseline reported by Idso et al (1981) at T_a = 30 C.

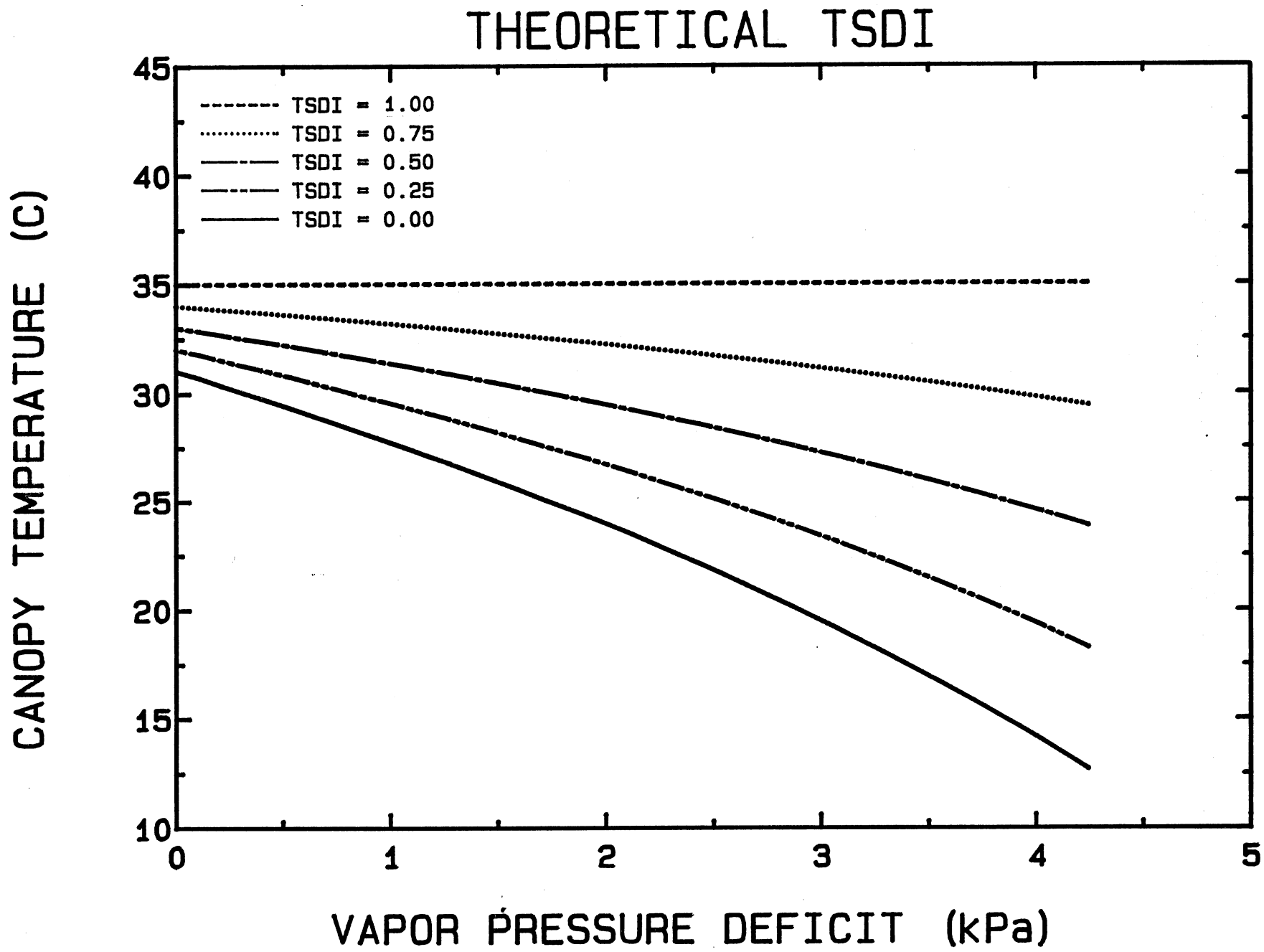
Fig. 5. Alfalfa canopy temperatures obtained under clear skies at 100% ground cover from all irrigation treatments for the period 15 Nov 1984 through 09 July 1985. Upper and lower limit lines denote empirically derived T_{cu} and T_{cL} from the non-water-stressed baseline reported by Idso et al (1981) and from the non-water-stressed baseline determined for these data.

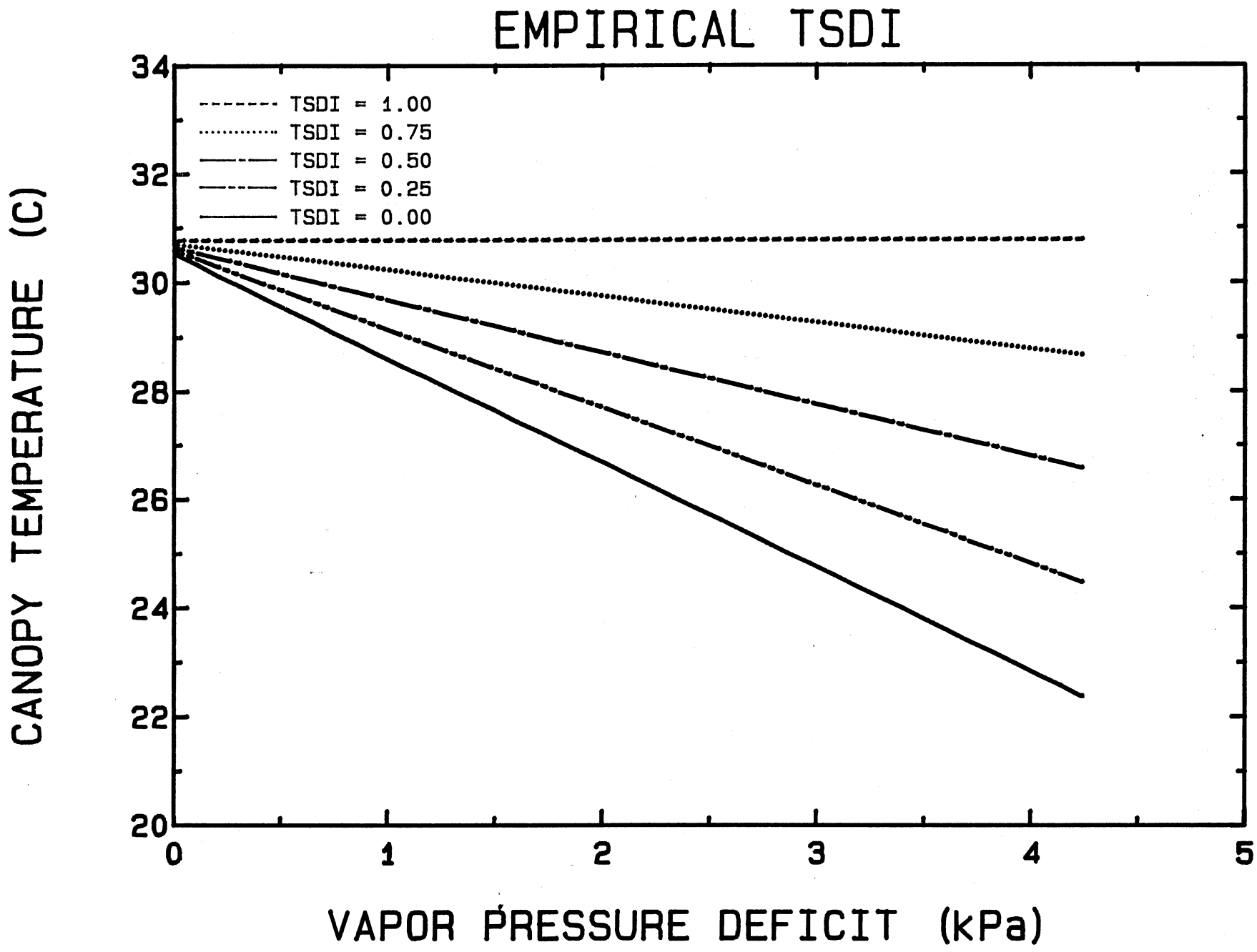
Fig. 6. Vapor pressure deficit dependence on air temperature as specified by a second order polynomial equation.

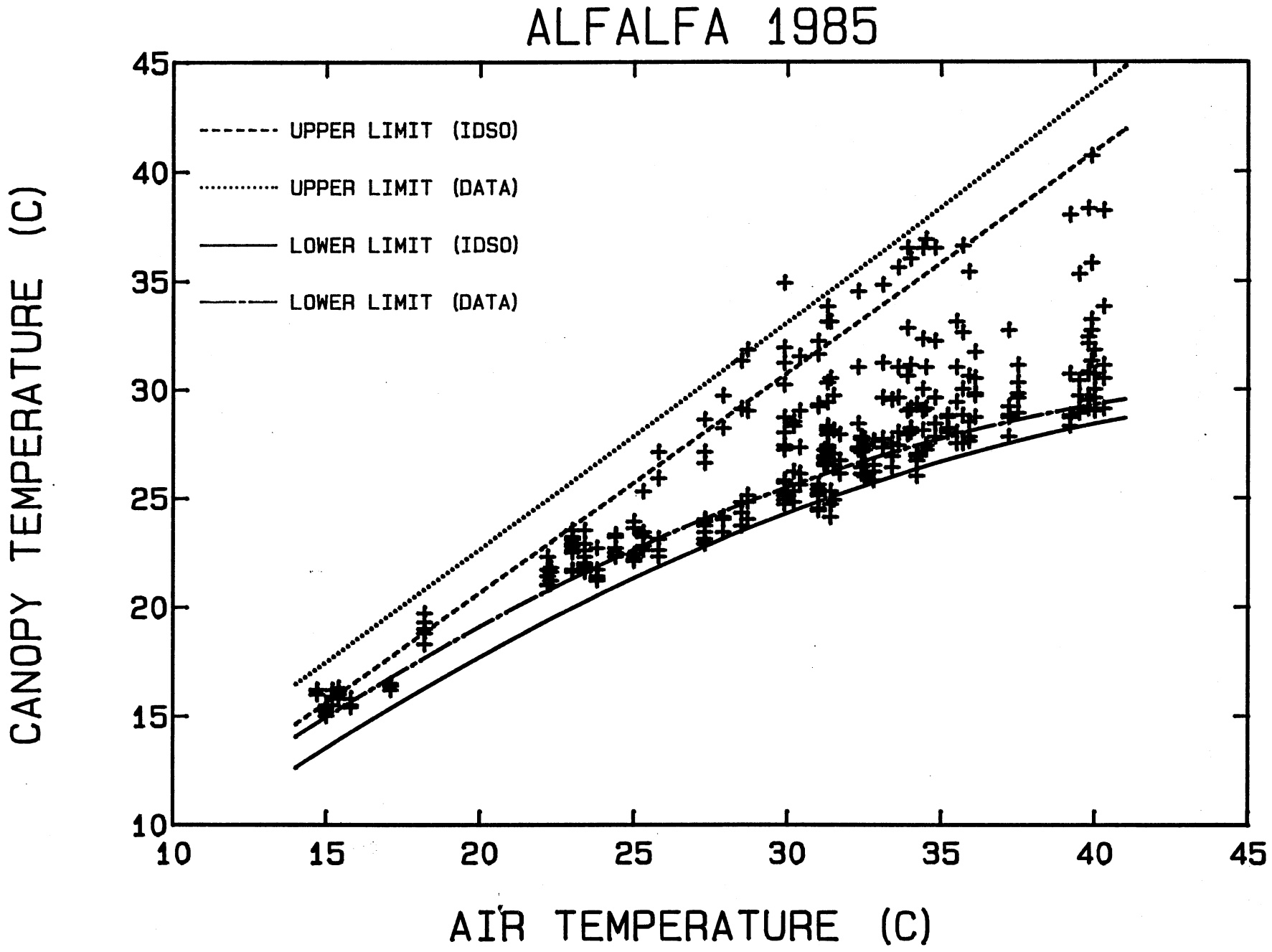
Fig. 7. As in Fig. 5 except upper and lower limit lines indicate theoretical T_{cu} and T_{cL} determined from iteration of Eqns. 4 and 5 by setting R_n = 600 W m^{-2} and using the T_a:VPD dependence as shown in Fig. 6.

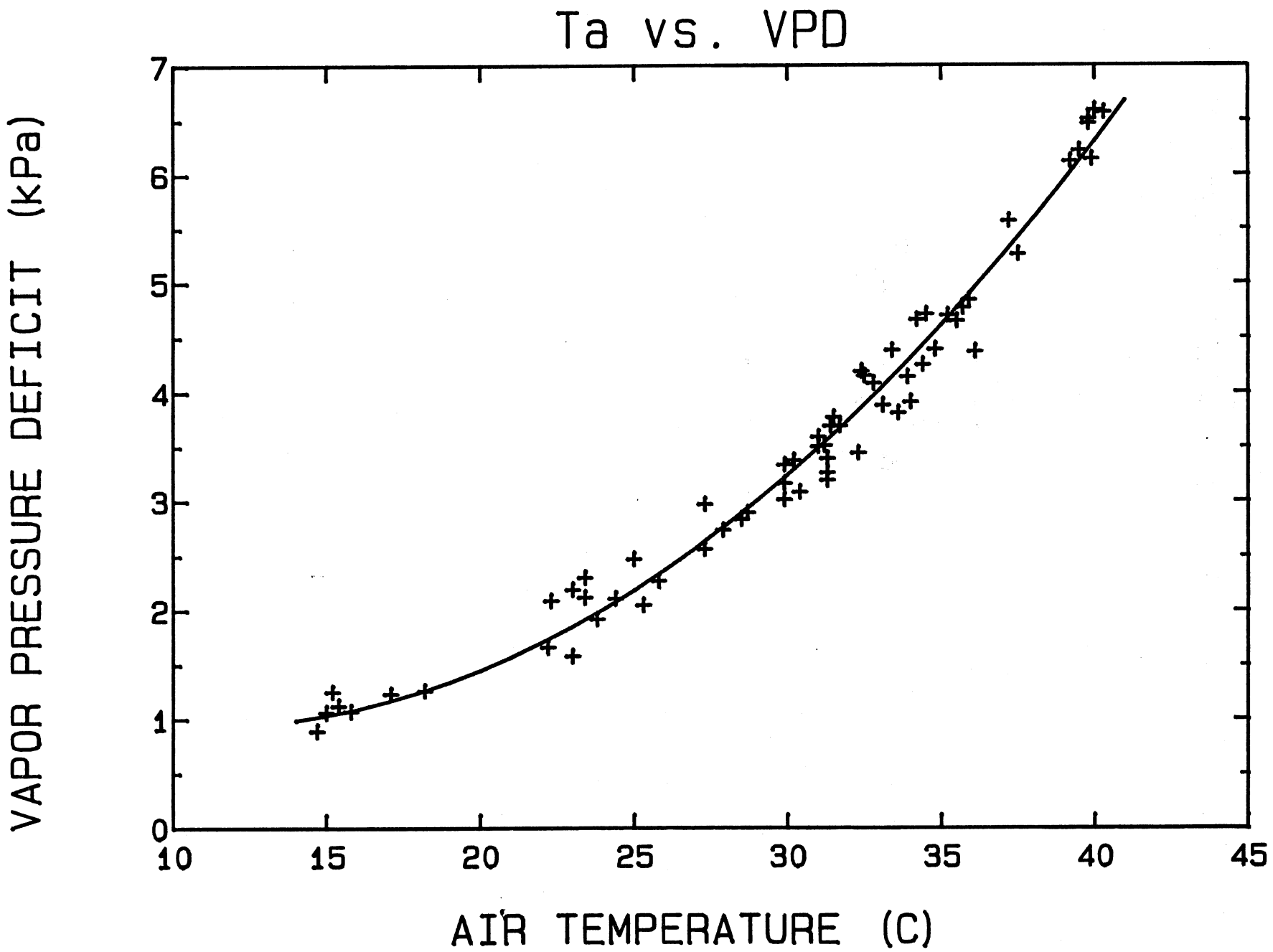

THEORETICAL LIMITS
UPPER LIMIT
LOWER LIMITS
100%
75%
50%
25%
10%
0%
CANOPY TEMPERATURE (C)
AIR TEMPERATURE (C)
0
5
10
15
20
25
30
35
40
45

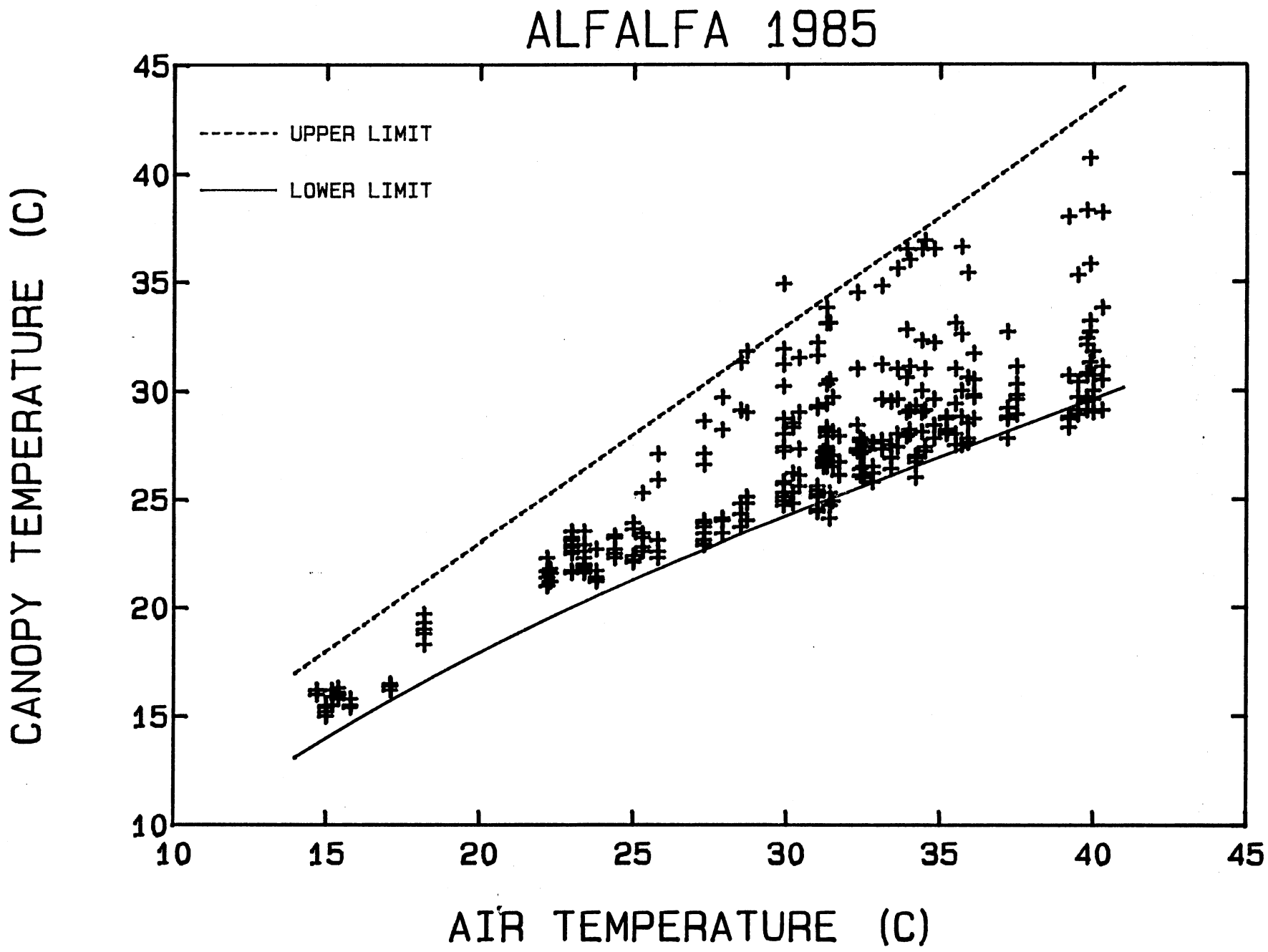

THEORETICAL LIMITS
TEMPERATURE DIFFERENCE (C)
RELATIVE HUMIDITY (%)
Ta = 40 C
Ta = 30 C
Ta = 20 C
Ta = 10 C
Ta = 0 C
0
5
10
15
20
25
30
0
10
20
30
40
50
60
70
80
90
100


THEORETICAL TSDI
TSDI = 1.00
TSDI = 0.75
TSDI = 0.50
TSDI = 0.25
TSDI = 0.00
CANOPY TEMPERATURE (C)
45
40
35
30
25
20
15
10
0
1
2
3
4
5
VAPOR PRESSURE DEFICIT (kPa)


EMPIRICAL TSDI
TSDI = 1.00
TSDI = 0.75
TSDI = 0.50
TSDI = 0.25
TSDI = 0.00
CANOPY TEMPERATURE (C)
34
32
30
28
26
24
22
20
0
1
2
3
4
5
VAPOR PRESSURE DEFICIT (kPa)


ALFALFA 1985
UPPER LIMIT (IDSO)
UPPER LIMIT (DATA)
LOWER LIMIT (IDSO)
LOWER LIMIT (DATA)
CANOPY TEMPERATURE (C)
AIR TEMPERATURE (C)
10
15
20
25
30
35
40
45


Ta vs. VPD
VAPOR PRESSURE DEFICIT (kPa)
AIR TEMPERATURE (C)
0
1
2
3
4
5
6
7
10
15
20
25
30
35
40
45


ALFALFA 1985
UPPER LIMIT
LOWER LIMIT
CANOPY TEMPERATURE (C)
AIR TEMPERATURE (C)
45
40
35
30
25
20
15
10
10
15
20
25
30
35
40
45

Dave

COMPARATIVE EVALUATION OF THE IDSO, JACKSON AND STANDARD OIL WATER STRESS INDICES

By
Bronson Gardner

The purpose of this report is to summarize the theoretical behavior of three methods for calculating crop water stress index (CWSI) values. The basis for this analysis stems from field observations made in 1986 field trials which indicate that under some circumstances the current method of calculating CWSI (the Idso method) yields results which are difficult to interpret. Consequently, an intensive theoretical analysis of three methods of computing CWSI was developed. Two of the methods (one by Idso and one by Jackson) have been published in the literature. The third technique is a proprietary method developed at Standard Oil.

Idso Index

Idso et al. (1981) proposed a technique for evaluating the severity of water stress exhibited by a crop. The technique was based on the assumption of a linear relationship between the minimum crop-air temperature difference (Delta-T) and the vapor pressure deficit of the air (VPD):

$$Min = a + b*VPD \quad (1)$$

A crop water stress index (CWSI) was defined as

$$CWSI = (Tc-Ta)-Min/(Max-Min) \quad (2)$$

where Tc = crop temperature
Ta= air temperature
max= theoretical maximum crop-air temperature difference

Max was calculated by a linear extrapolation based of the Min line into the negative VPD region.

This approach assumes that the coefficients a and b are independent of net radiation (Rn) and air temperature effects. Evaluating the coefficients for a given crop can be a difficult task , often requiring several days worth of data, although there are times when meteorological conditions provide a sufficient range in VPD to determine a and b from hourly data collected on a single day. In spite of these difficulties, the Idso approach is appealing because of it's computational simplicity and because no windspeed or radiation terms are included in the index.

Jackson Index

By contrast, Jackson et al. (1981) proposed a CWSI based on the energy balance equation. Jackson et al. (1981) proposed that Min be calculated as :

$$Min = \frac{ra*Rn*g(1+rc/ra)}{Rho*cp*d+g(1+rc/ra)} - \frac{VPD}{d + g(1+rc/ra)}$$

where ra is the aerodynamic resistance of the crop , rc is the canopy resistance to vapor transport, g is the psychrometric constant, d is the slope of the saturated vapor pressure curve, VPD is the vapor pressure of the air, Rn is net radiation , Rho is the density of air, and cp is the heat capacity of air. Max was calculated as :

$$Max = ra*RN/(Rho*cp) \quad (3)$$

Jackson et al. (1981) recommended that the ratio rc/ra be evaluated with the following equation :

$$rc/ra = \frac{[g*ra*rn/(Rho*cp)] - (Tc-Ta)*(d+g)-VPD}{g^* [(Tc-Ta) - ra*Rn/(Rho*cp)]} \quad (4)$$

After rc/ra was calculated using this procedure, CWSI was calculated :

$$CWSI = \frac{g * (1+rc/ra)- g*(1+rcp/ra)}{d + g*(1 + rc/ra)} \quad (5)$$

where rcp is the crop resistance at potential transpiration rates for a given crop. It can be seen that algorithms are also needed for estimating aerodynamic resistances and rcp values, in addition to the necessity of measuring net radiation and windspeeds. For this analysis, rc/ra was assumed to be 0.5 and rcp was set equal to 0.

Standard Oil's Index

Standard Oil has developed a proprietary index which serves as an alternative to the Idso and Jackson equations. Evaluation of this index requires inputs of Tc, Ta, relative humidity and net radiation as a percent of the maximum expected net radiation. Evaluation of the coefficients in this index also requires a knowledge of the maximum crop-air temperature difference for a given crop at high air temperatures.

Comparison Between the Indices

In order to evaluate the overall performance of the Idso, Jackson and Standard Oil indices, it was necessary to generate a standard data set. In this standard data set, Rn was varied between 50 and 750 w/m^2, in units of 50; Ta was varied between 15.6 C (60 F) and 43.3 C (110 F) in steps of 5.6 C (10 F); Tc-Ta ranged between -7.5 C to 22.5 C in steps of 2.5 C ; VPD ranged between 0 and 5 kPa in steps of 0.2, providing the VPD value at a given Ta did not exceed the saturated vapor pressure, errors in measuring Tc (Ec) or decreases in Tc due to changes in Rn ranged between 1 and 3 C. This data set contained 15210 combinations of Rn, Ta, (Tc-Ta), VPD and Ec. It should be remembered that the theoretical ranges in all three indices is between 0 and 1.

The Idso index was evaluated for corn by using coefficients given in Idso (1982), with Tc-Ta limited to a maximum of 12 c. This standard data set showed that the Idso index is well behaved above VPD values of about 2.0. Below VPD values of 2.0, the Idso scale rapdily expands to -12 to +12 . The consistency of the scale above VPD's of 2.0 makes the Idso scale useable within these limitations. In practice, this would mean that the meteorological conditions under which the Idso index could be used accurately are well defined (Table 1).

The Idso index was also extremely sensitive to errors in measuring Tc or to changes in Tc as a result of fluctutions in Rn (figure 2). The scale on this index also is a function of the magnitude of the value of Tc-Ta (figure 3). These results show that unless the Idso index is used in relatively hot dry climates (high VPD values) and unless Tc , Ta, and VPD are measured accurately under sunny conditions that significant difficulty in interpreting Idso's CWSI can occur.

Table 1 . Approximate regions where the Idso index provides consistent results.

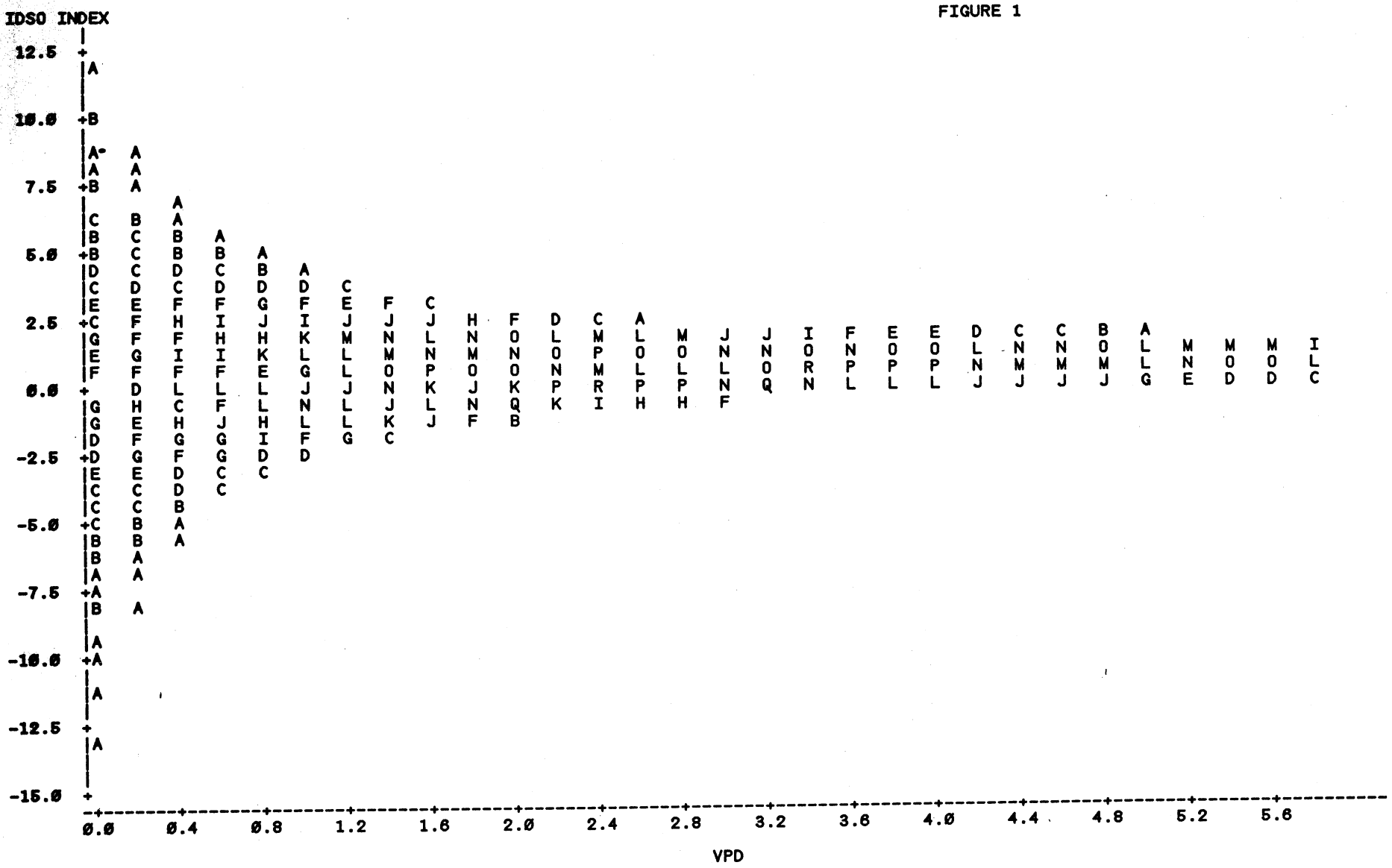
Air temperatures must be greater than	and	Relative humidity must be less than
68.0 F		14 %
75.2 F		33 %
82.4 F		47 %
89.6 F		58 %
96.8 F		66 %
104.0 F		73 %
111.2 F		78 %

The behavior of the Jackson index is similar to that of Idso (Fig. 4 -7). Jackson's index is a strong function of net radiation and vapor pressure deficit. The scale of the index ranges between -8 and +14 at low VPD values. The index is an improvement over the Idso index, however. Note that the errors caused by decreases in canopy temperature (or errors in Tc) are more systematic than those of in the Idso equation.

The foregoing analysis is the basis for the new CWSI index . This new index has a nearly flat scale between over the entire net radiation and vapor pressure deficit ranges on which it was tested (Fig 8-9). As Tc changes due to errors or reductions in Rn, index values decrease by a maximum of only 0.4 (as compared to several times 0.4 for the Idso and Jackson indices) (Fig 10). The relationship between the new CWSI and Tc-Ta is linear (Fig 11). At any given value of Tc-Ta, there is a clearly defined minimum and maximum value of CWSI. The exact value is then dependent on net radiation and VPD. Research using this new index has begun.

RESPONSE OF IDSO INDEX TO VPD
CROP = CORN

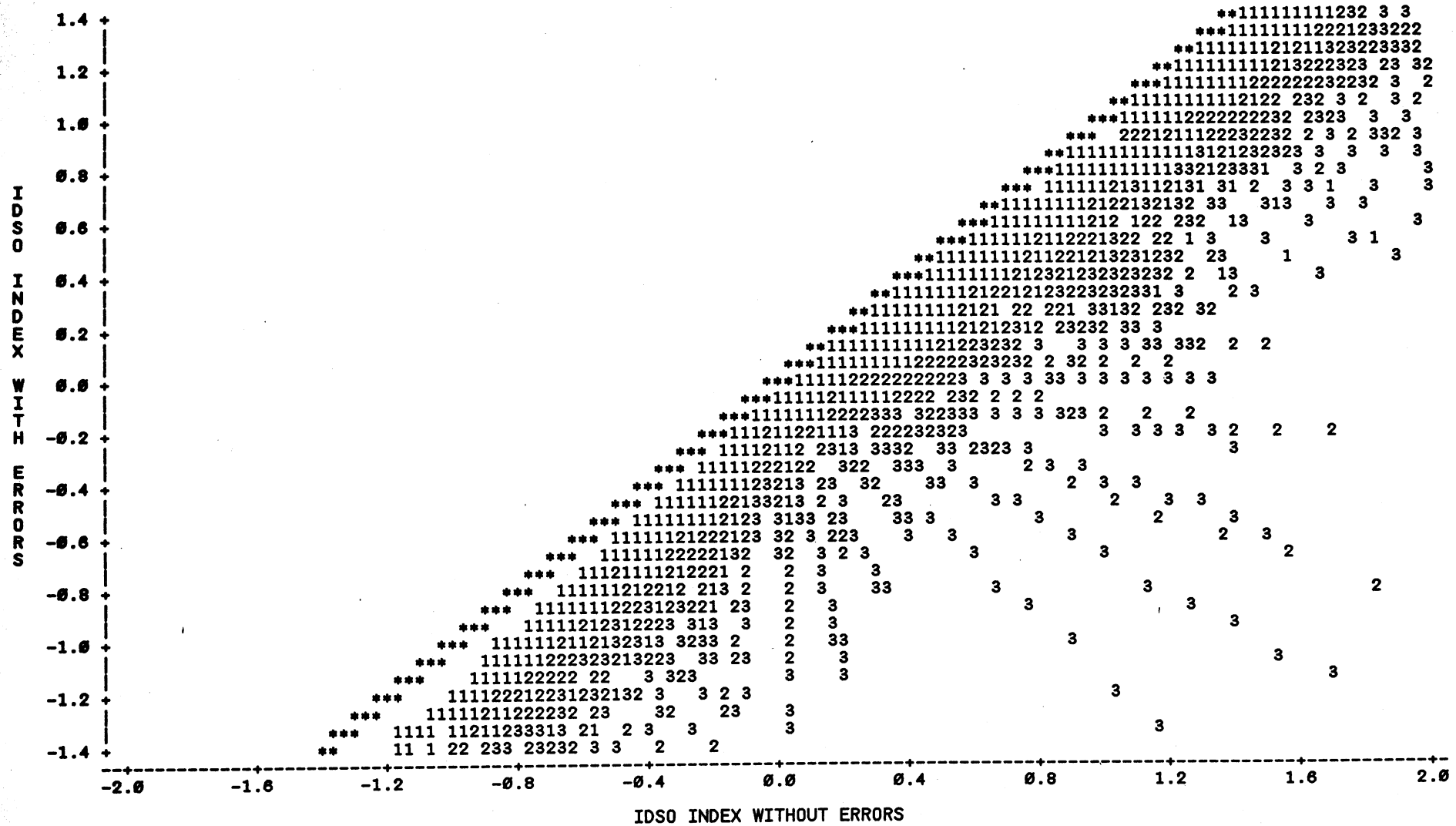
FIGURE 1



RESPONSE OF IDSO INDEX TO ERRORS/CHANGES IN CROP TEMPERATURE
CROP TEMP ERRORS/CHANGES OF 1 TO 3 C
CROP = CORN

SYMBOL IS VALUE OF ERROR/CHANGE
SYMBOL IS VALUE OF ERROR/CHANGE
SYMBOL IS VALUE OF ERROR/CHANGE
1:1 LINE -- SYMBOL USED IS *

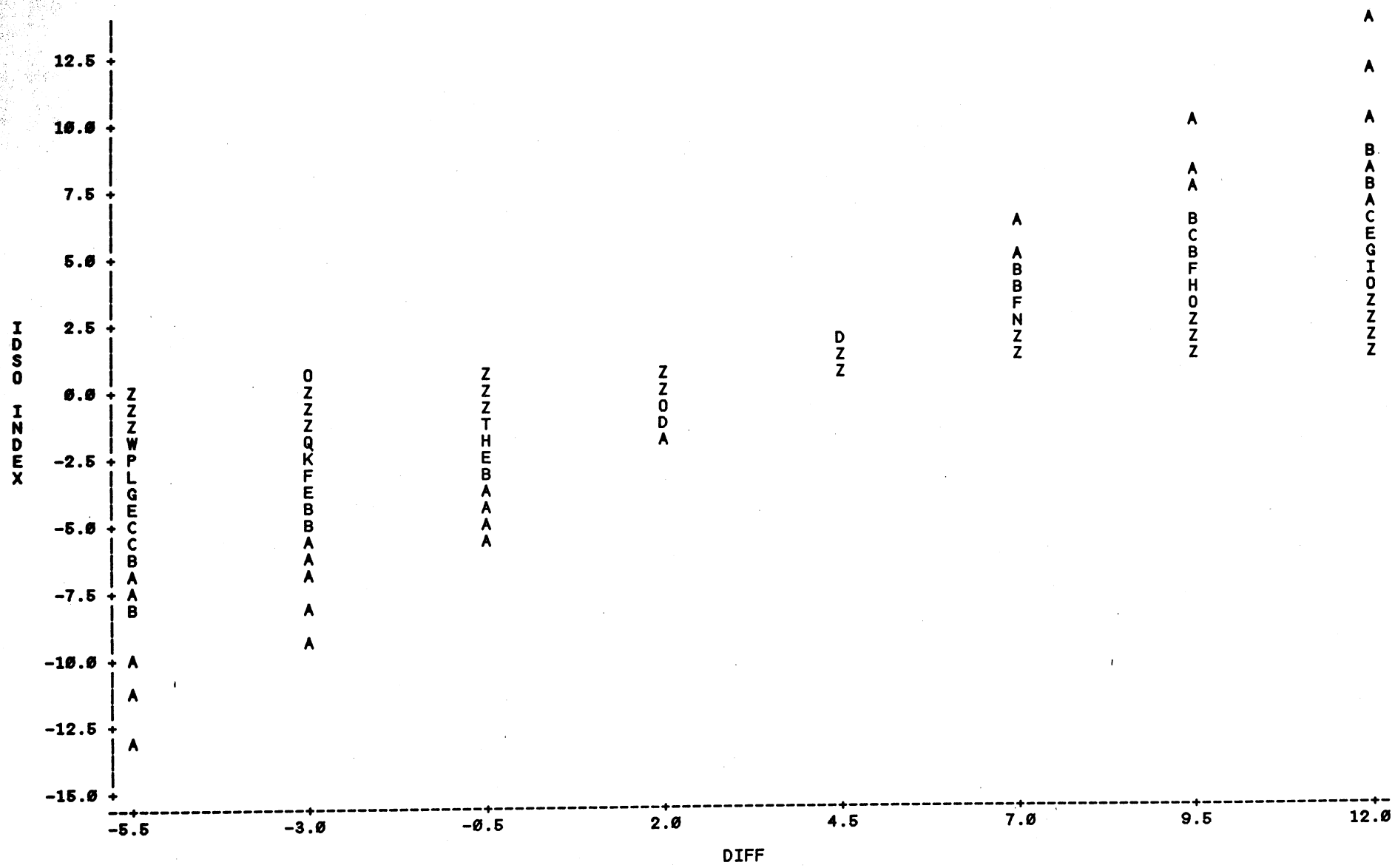
FIGURE 2



NOTE: 2607 OBS HAD MISSING VALUES OR WERE OUT OF RANGE 3923 OBS HIDDEN

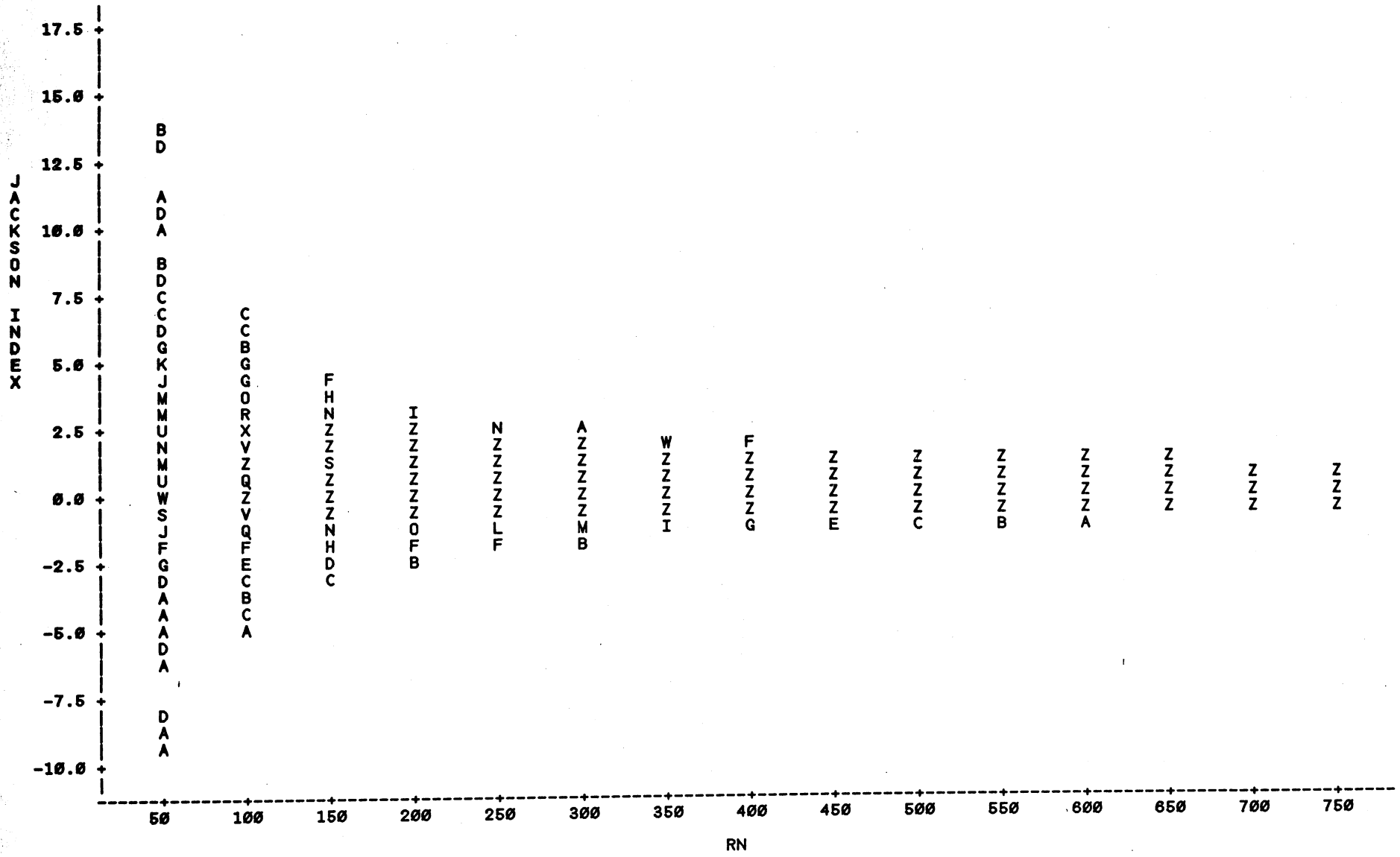
RESPONSE OF IDSO INDEX TO TC-TA
CROP=CORN

FIGURE 3



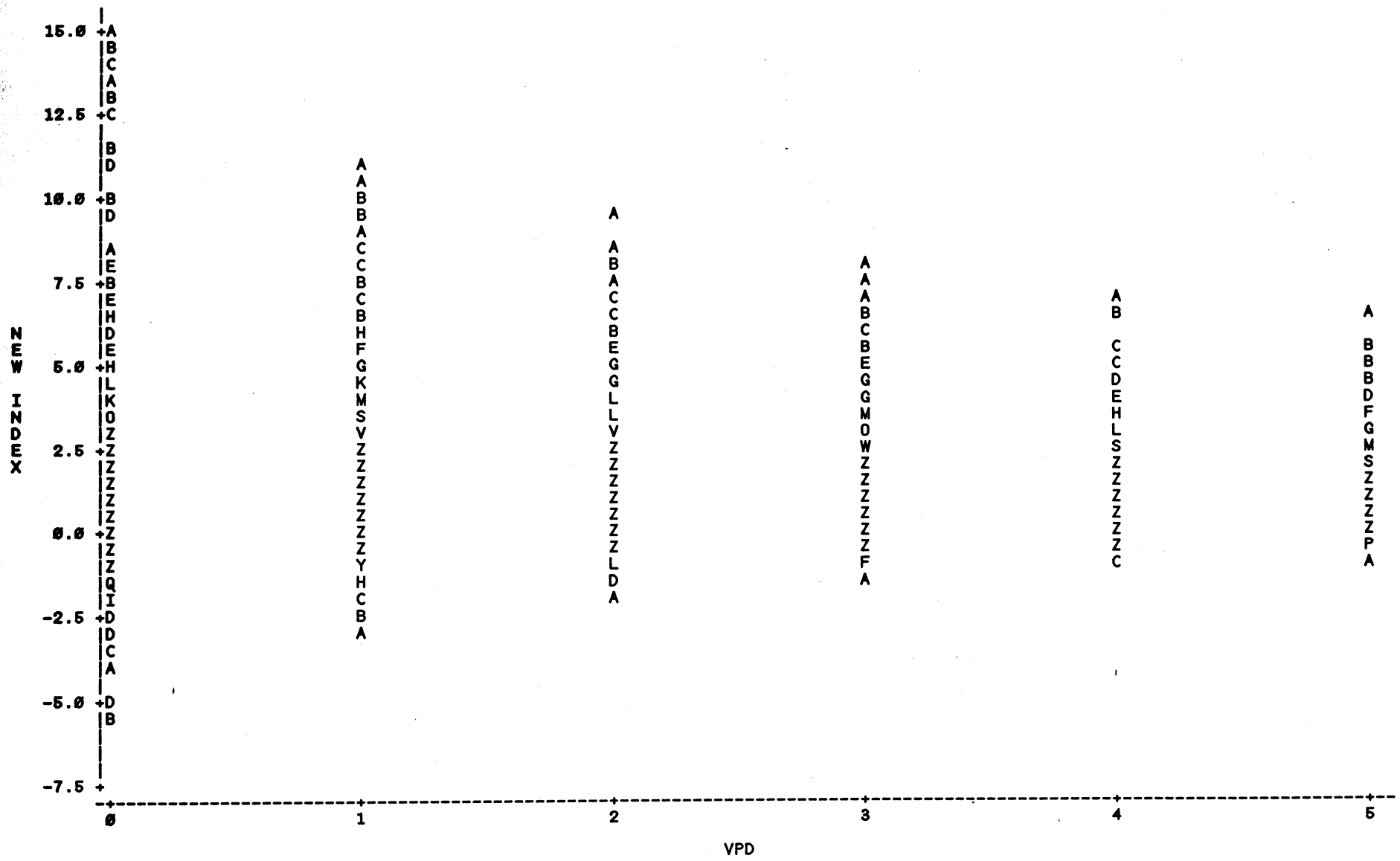
JACKSON INDEX VERSUS NET RADIATION
CROP=CORN

FIGURE 4



JACKSON INDEX VERSUS VPD
CROP=CORN

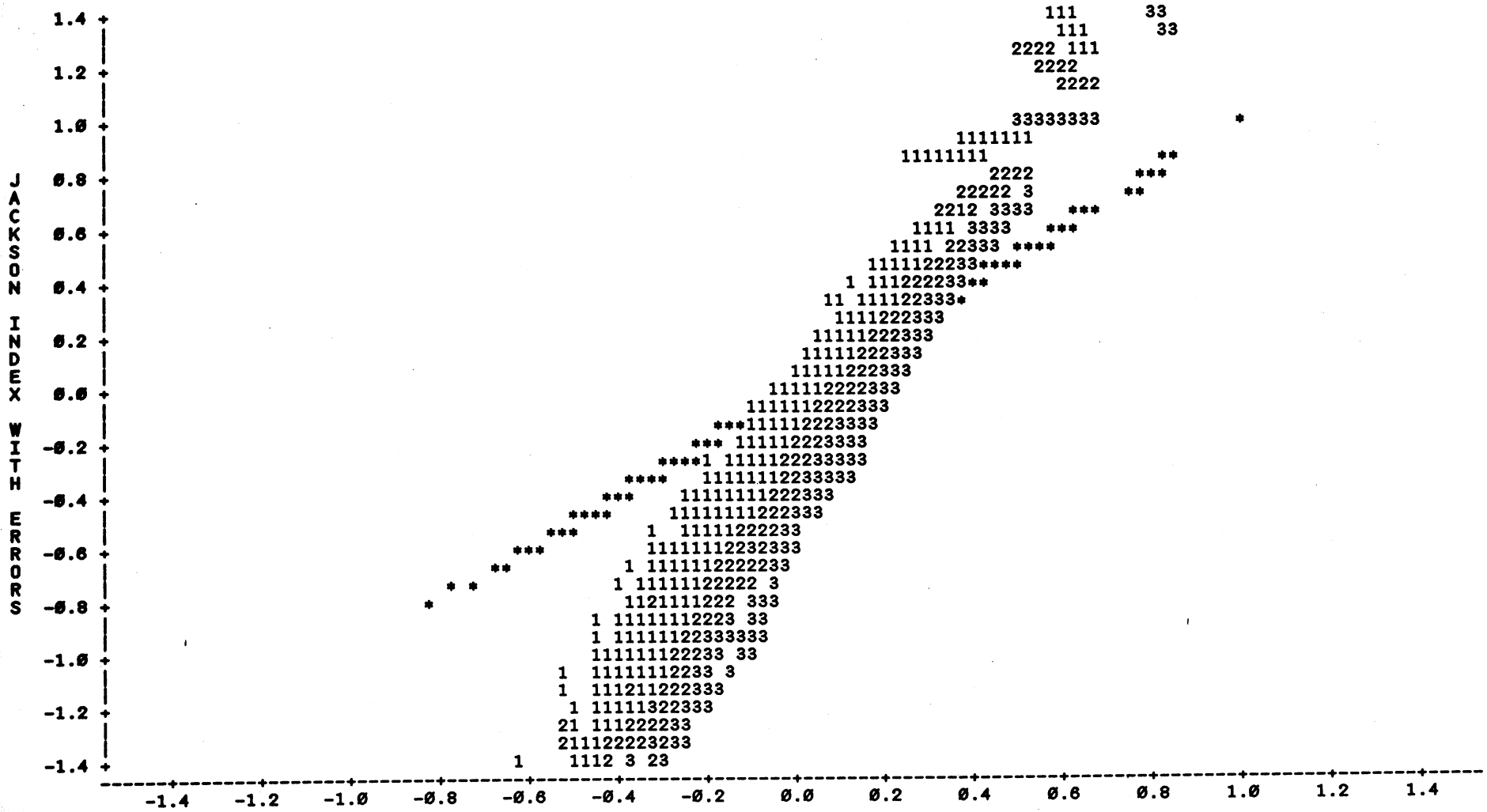
FIGURE 5



RESPONSE OF JACKSON INDEX TO A REDUCTION IN RN
RN DECREASES FROM 600 TO 200 W/M2, CROP TEMP DECREASES FROM 1 TO 3 C
CROP=CORN

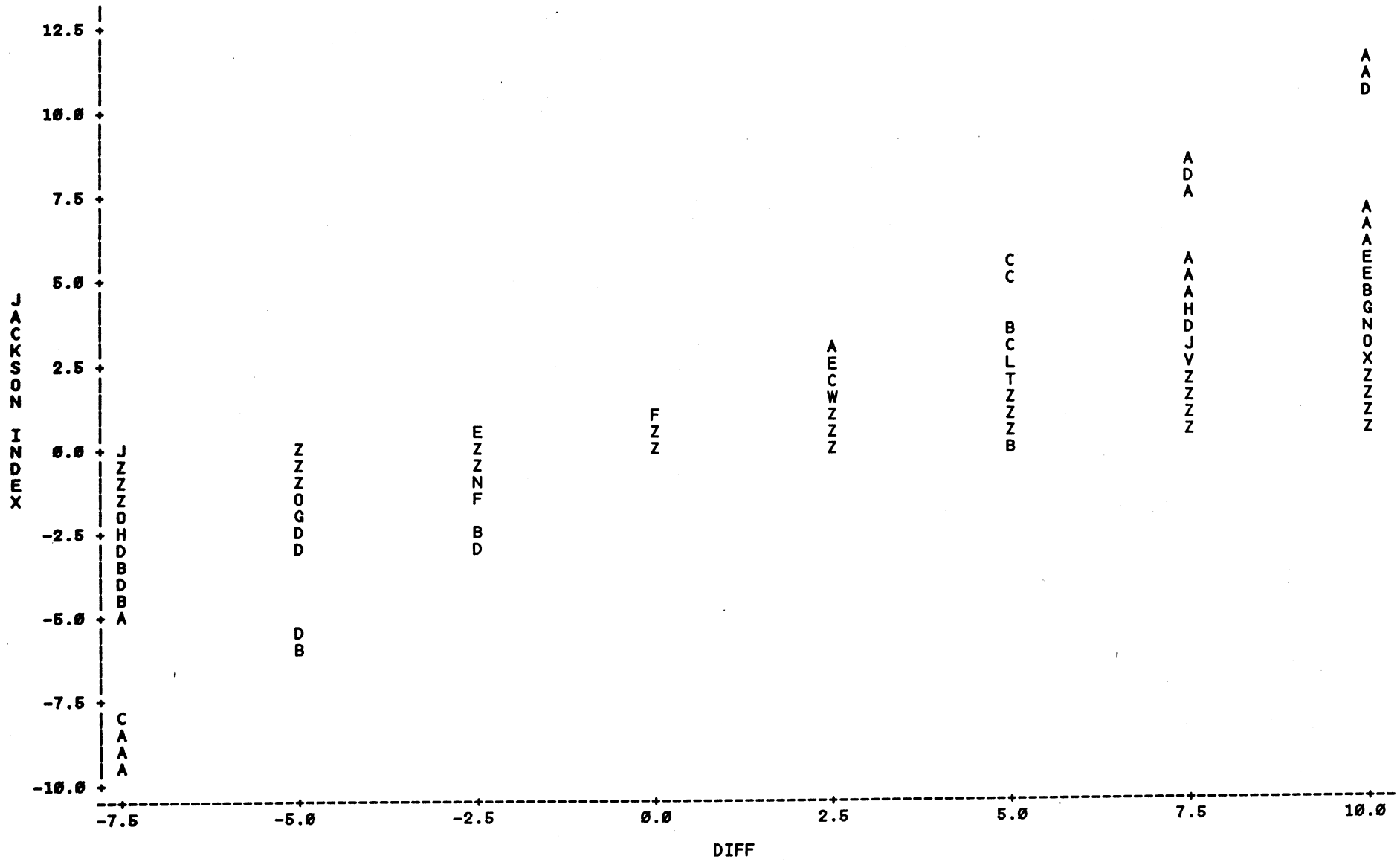
SYMBOL IS VALUE OF ERROR/CHANGE IN TC
SYMBOL IS VALUE OF ERROR/CHANGE IN TC
SYMBOL IS VALUE OF ERROR/CHANGE IN TC
1:1 LINE-- SYMBOL USED IS *

FIGURE 6



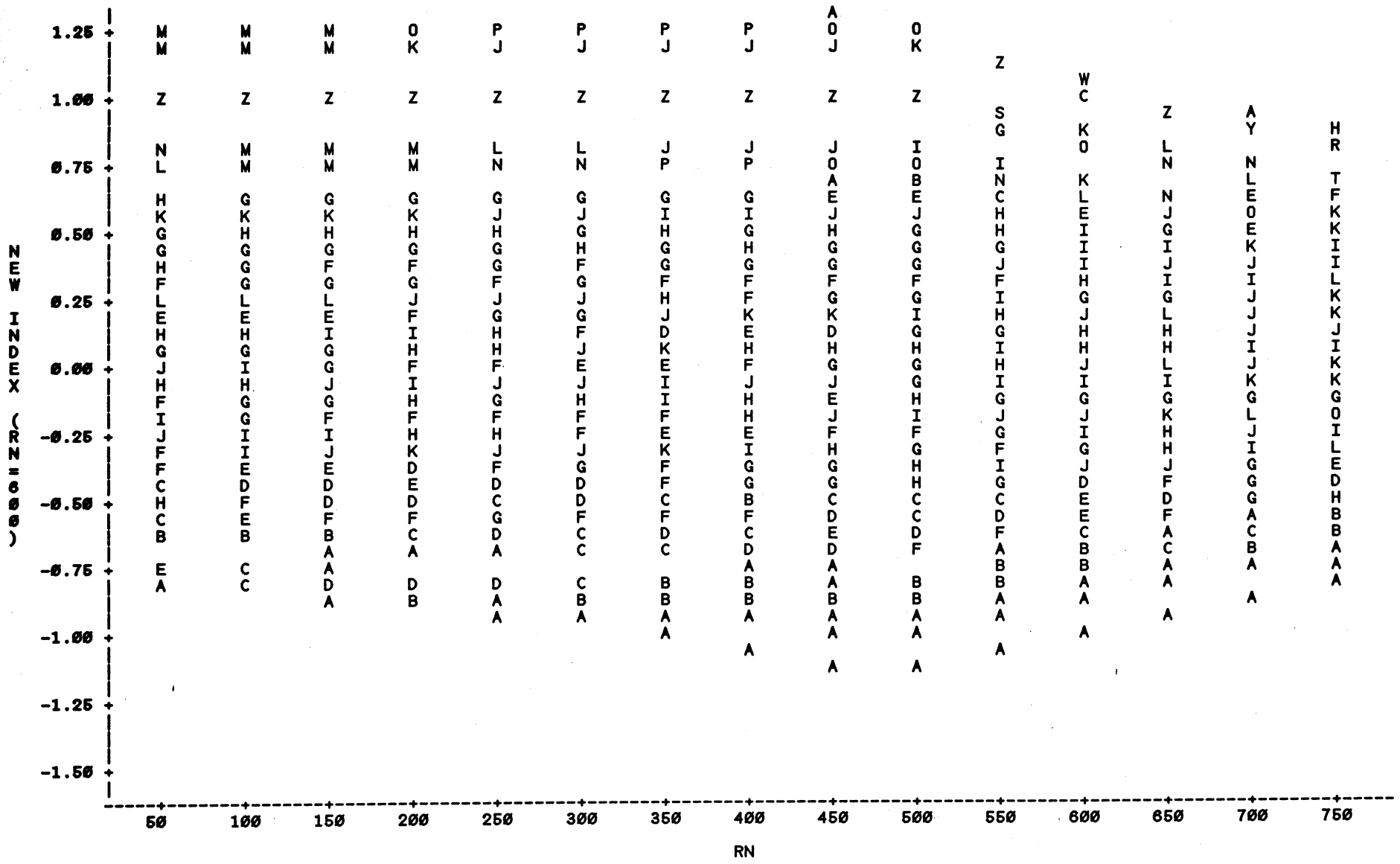
JACKSON INDEX VERSUS TC-TA
CROP=CORN

FIGURE 7



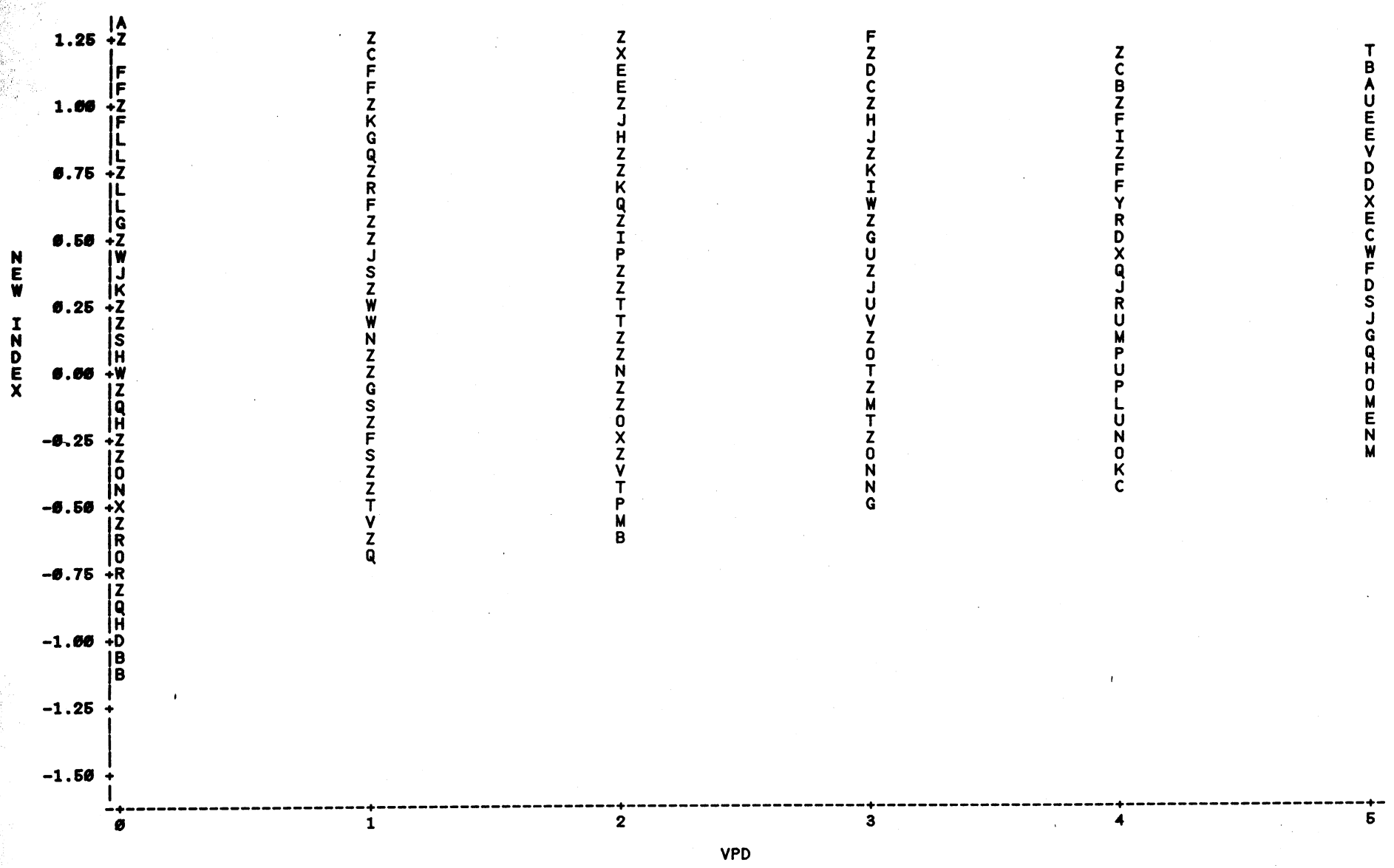
NEWCWSI VERSUS NET RADIATION
CROP=CORN

FIGURE 8



NEWCWSI VERSUS VPD
CROP=CORN

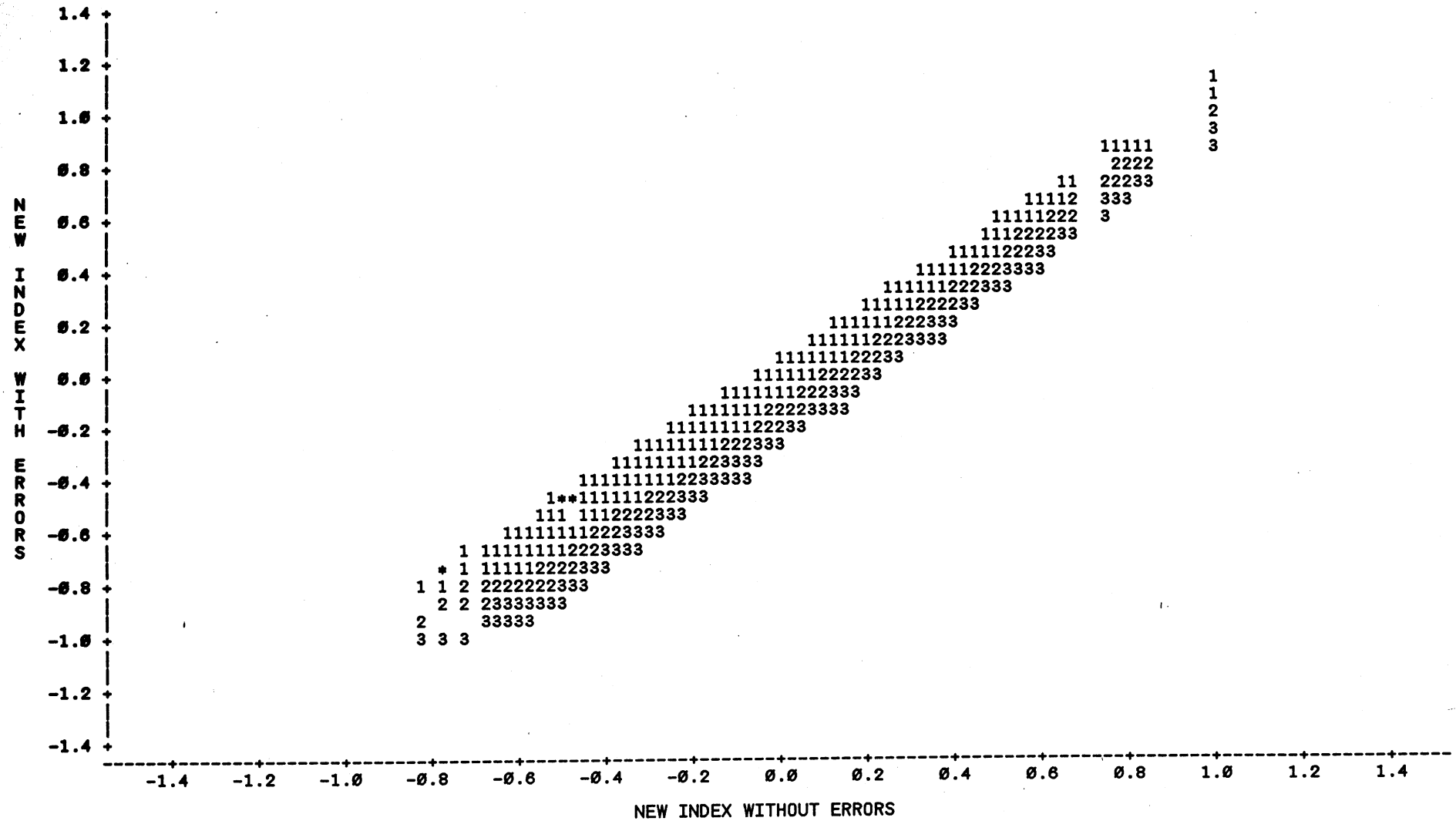
FIGURE 9



RESPONSE OF NEW INDEX TO A REDUCTION IN RN
RN DECREASES FROM 600 TO 200 W/M2, CROP TEMP DECREASES FROM 1 TO 3 C
CROP=CORN

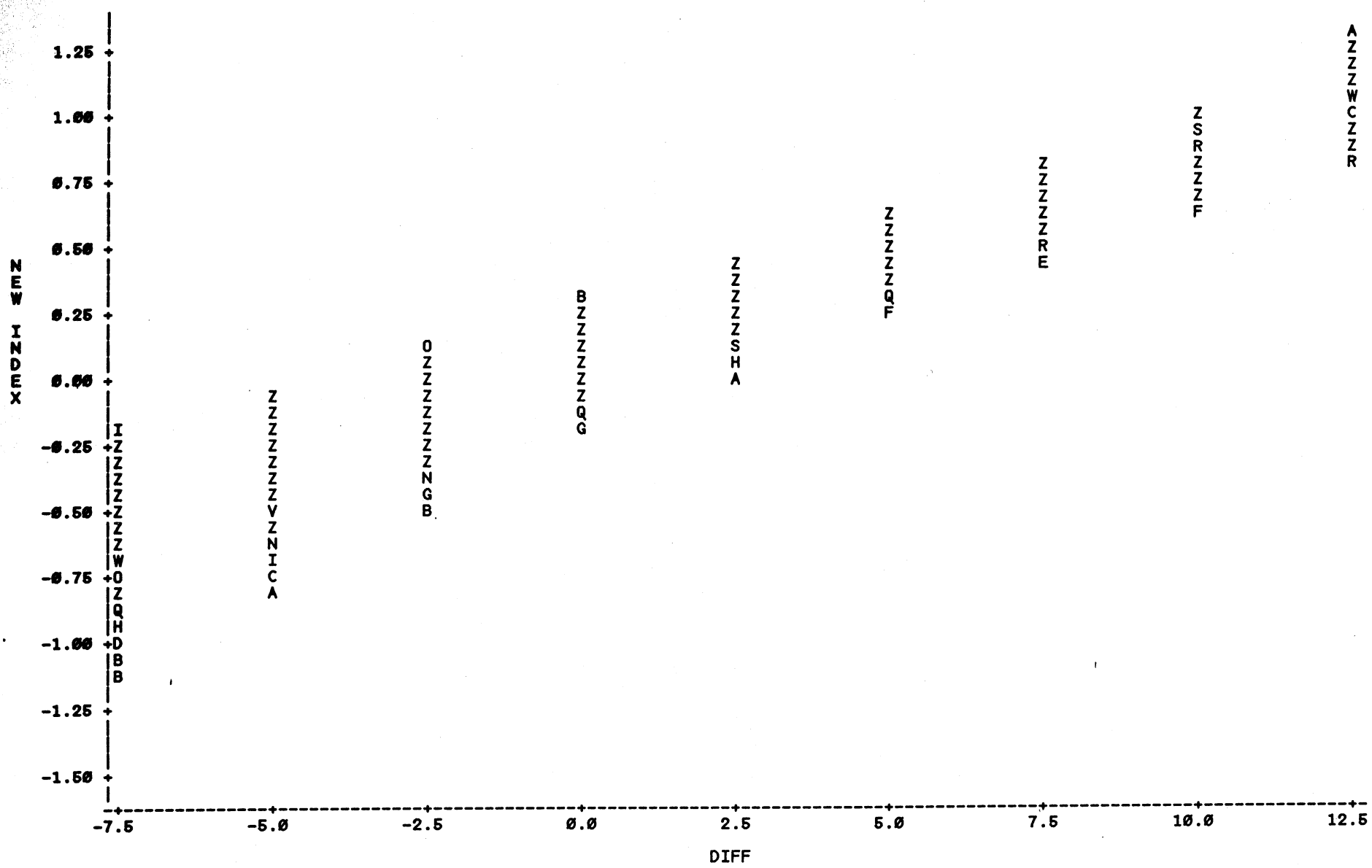
FIGURE 10

SYMBOL IS VALUE OF DECREASE
SYMBOL IS VALUE OF DECREASE
SYMBOL IS VALUE OF DECREASE
1:1 LINE -- SYMBOL USED IS *



RESPONSE OF NEW INDEX TO TC-TA
CROP=CORN

FIGURE 11



References

Idso, S.B., Jackson, R.D., Pinter, P.J., Jr., Reginato, R.J. and Hatfield, J.L. 1981. Normalizing the stress degree day for environmental variability. Agric. Meteor. 24:45-55.

Idso, S.B. 1982. Non-water stressed baselines: a key to measuring and interpreting plant water stress. Agric. Meteor. 27: 59-70.

Jackson, R.D., Idso, S.B., Reginato, R.J. and Pinter, P.J., Jr. 1981. Canopy temperatures as a crop water stress indicator. Water Resour. Res 17: 1133-1138.

STANDARD OIL
ENGINEERED MATERIALS

Memorandum

To: S. C. DeSutter Date: 11/9/87

From: B. R. Gardner Copy to:

B. R.

Subject: Improved Technique for Measuring Non-Stressed Baseline Values

I believe we should incorporate an alternate index into our options. There are users who complain about inconsistency in the current index. Inconsistencies are the result of errors in estimating the true minimum temperature of a crop for a given day. The factors which may cause these errors include:

Factor

Sunlight variability
Percent ground cover
Windspeed variations
CO_2 variations
(This factor, just recent discovered) CO_2 varies with soil moisture and the amount of decomposing organic matter.
Age of Crop
Sampling technique
Time of day
Genotype
Surface wetness of the soil
Instrument differences
Air temperature fluctuations
Baseline errors

It is probable that no mathematical model will be developed in the near-term which can remove all these sources of variability. It is also clear that Scheduler sales/reputation hinge on the ability to absolutely minimize all sources of variability not associated with transpiration. In other words, the Scheduler index must be consistent despite all aforementioned potential sources of error.

There is a way to accomplish this objective. I have tested this method on the cucumber data from Wisconsin and am convinced that this procedure should become a part of our options in selling/using the Scheduler.

The method requires a user to identify an area which has been recently irrigated (a piece of information which requires very little judgment). The user would simply walk into this area and take 30-40 samples. No index would be produced at this point. The user has just calibrated his baseline to adjust it to all the aforementioned sources of variability, including instrumentation.

How is this done since the stress status of the field is not known (but by definition it should not be in a severely stressed status)? After the samples are taken, the CPU calculates the mean and standard deviation of the crop temperature and the mean sunlight level. The quantity [(Tc-Ta) - Std] for a reasonably non-stressed field is the minimum baseline.

How would this change the way in which the current index is calculated?

The current index is:

$$10 * (Diff - Min)/ (Max - Min)$$

where $Min = a + b * VPD$

The new index is:

$$10 * (Diff - NMin) / (Max - Min)$$

where NMin is the statistical minimum

As you can see, the denominators are identical, since the denominator represents the potential spread between stressed and non-stressed plants. All that has been done is to substitute a statistically measured value for Min in pace of a computed value based on VPD. The suggested substitution can be expected to greatly improve the stability of the index.

BRG/lb

12 April 1988

Orange Index – New Concept

general

$$\text{Index} = 10\left[1 - \frac{ET}{ETp}\right]$$

(1) ET estimate

$$ET = R_N - \frac{\rho c_p}{r_a}(T_c - T_a)$$

$R_N = 0.77 R_S - \sigma T_c^4$

$\rho c_p = 1294.1$

$\sigma = 5.67 \times 10^{-8}$

$r_a = 50 - 4.0\,U$ (U is in mpH)

if wind = 0 (mpH), $r_a = 50$

if wind = 1–5, $r_a = 35$

if wind = 5–10 $r_a = 20$

if wind ≥ 10 $r_a = 10$

(2) ET_p estimate

$$ET_p = \frac{\Delta}{\Delta+\gamma} R_N + \frac{\gamma}{\Delta+\gamma} \cdot f(u) \cdot VPD$$

$f(u) = 0$, if wind = 0

$f(u) = 15$ if wind 1–5

$f(u) = 35$ if wind 5–10

$f(u) = 50$ if wind ≥ 10

$f(u) = 4.9$ (wind) (wind is in mph)

$= 4.9 * u$

(2) continued

(2) $R_N = 0.77 \cdot R_S$

$R_S = f(\text{Latitude, Day of year})$ ≈ 1000 for Oranges
Leaf ⊥ to Sun

$$\Delta = VPS \left[\frac{4098.025\,82}{(T_A + 237.3)^2} \right]$$

VPS = already in Scheduler

$$= 0.61078 \times EXP \left[\frac{17.269\,3882 * T_A}{T_A + 237.3} \right]$$

$\gamma = 0.066$

(3) $$Index = \left[6.0 - 10 * \frac{ET}{ET_p} \right]$$

Note K_c of Oranges ≈ 0.6 all year

$K_c = 0.6$ = Index of 6

ORANGES
4.74 – 1.27 VPD, Max = 8